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# Protection of Department of Defense Facilities from Airborne CBR Threats

## An Annotated Bibliography

David M. Bailey, Dahtzen Chu, Dale L. Herron, David M. Schwenk,  
Chang W. Sohn, and David M. Underwood

September 2004



Work continues in support of Operation Enduring Freedom during a gas mask familiarization exercise in Kuwait.



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## **Final Report**

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**ABSTRACT:** Department of Defense policy is to protect all military and civilian personnel on military installations against chemical, biological, radiological, nuclear, and high-yield explosive (CBRNE) attacks, specifically “to protect personnel on military installations and DOD-owned or leased facilities from CBRNE attacks, to respond to these attacks with trained and equipped emergency responders, and to ensure installations are able to continue critical operations during an attack and to resume essential operations after an attack.

Compliance with this memorandum, however, will be an enormous undertaking. Existing technologies that will enable DOD to fully implement its CBRNE protective policy must be identified and validated. Technology gaps in DOD’s ability to respond to and resist specific CBR threats must be identified, and solutions that fill those gaps must be developed. This work summarizes past and current research in target technological areas, with a focus on three CBR protection sub-areas: (1) modeling and simulation of airborne chemical/biological contaminant dispersion in a building, (2) intelligent building control, and (3) CBR-related whole building diagnostics.

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## Conversion Factors

Non-SI\* units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	$(5/9) \times ({}^{\circ}\text{F} - 32)$	degrees Celsius
degrees Fahrenheit	$(5/9) \times ({}^{\circ}\text{F} - 32) + 273.15$	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

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\* *Système International d'Unités* ("International System of Measurement"), commonly known as the "metric system."

## Preface

This study was conducted for the Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 622784T45, “Energy Technology Applied to Military Facilities”; Work Item 52LFB8, “CBRN Protection of Facilities Work Package.” The work package includes Work Item 41JGDG, “Intelligent Building Control Systems” and Work Item GD1KGD, “Building Chem-Bio Protection Modeling & Simulation.” The technical reviewer was Dr. Paul A. Howdyshell, CEERD-CV-T.

The work was performed by the Energy Branch (CF-E) and the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL project managers were David M. Schwenk (CF-E) and Dr. William J. Croisant (CF-F). Dr. Tom Hartranft, Chief, CF-E is the CERL work package leader. Martin J. Savoie is Chief, CF-M, Mark Slaughter is Chief, CF-F, and L. Michael Golish is Chief, CF. The associated Technical Director is Dr. Paul A. Howdyshell. The technical editor was William J. Wolfe, Information Technology Laboratory. The Director of CERL is Dr. Alan W. Moore.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL James R. Rowan, and the Director of ERDC is Dr. James R. Houston.

# 1 Introduction

## Background

Following the delivery through the U.S. mail of anthrax-laced letters in 2001-2002, the threat of chemical, biological, and radiological (CBR) terrorist attacks in U.S. buildings has become recognized as a credible possibility. Department of Defense policy is to protect all military and civilian personnel on military installations against chemical, biological, radiological, nuclear, and high-yield explosive (CBRNE) attacks. The Deputy Secretary of Defense (DepSecDef) Memorandum, *Preparedness of U.S. Military Installations and Facilities Worldwide Against Chemical, Biological, Radiological, Nuclear and High-Yield Explosive (CBRNE) Attack* (05 September 2002) stated that:

It is the policy of the Department to protect personnel on military installations and DOD-owned or leased facilities from CBRNE attacks, to respond to these attacks with trained and equipped emergency responders, and to ensure installations are able to continue critical operations during an attack and to resume essential operations after an attack.

The memo further stated that:

This includes protection for military personnel, DOD civilians, other persons who work on the installations and facilities, and family members assigned overseas or who work or live on our installations and facilities worldwide.

The objective for personnel deemed essential to the performance of critical military missions (whether military, civilian, contractor, host nation personnel or third country nationals) will be to provide the appropriate level of protection necessary to support mission continuity.

For all other persons, the objective will be to provide protection or procedures necessary to safely survive an incident.

Compliance with this memorandum will be an enormous task. The Army alone has thousands of buildings distributed among 171 installations worldwide (U.S.

Army Installation Management Agency [IMA], data accessed through URL: <http://www.ima.army.mil/index.asp>). Providing protection to the Army's building infrastructure to make them less susceptible to and better able to respond to potential CBR attacks will be a complex undertaking.

The design and construction of buildings (or their retrofit) to provide protection against chemical, biological, and radiological (CBR) threats is a new and evolving challenge involving many factors. Collective protection against an external release attack has received significant attention. Some guidance on "passive" protection is available (HQUSACE 24 February 1999; HQUSACE, October 2001; DOD 8 October 2003). The same is not true for protection of building occupants against an active/hostile internal release of an airborne CBR agent. This problem is particularly challenging because of the large number of variables involved in preventing, detecting, or treating the results of such an occurrence, e.g., building configuration, building use, CBR release scenarios, and type(s) of CBR agents. In addition to conventional chemical warfare agents, potential terrorists may also use relatively easy to obtain toxic industrial chemicals such as ammonia and chlorine or pesticides. "Would-be terrorists have a much longer list of agents from which to choose than does a military force ... There is no terrorist "rule-book" that limits their chemical choices to the same list used by the military" (Wrenn 2004).

A number of options might be considered for a particular building. The potential solution set ranges from simple detection to sophisticated autonomous systems with the ability to automatically detect, analyze, and respond to a CBR attack. For example, the Defense Advanced Research Projects Agency (DARPA) Immune Building Program is currently investigating options to reduce the effectiveness of an attack via dynamic response of heating, ventilating, and air conditioning (HVAC) (and other) building infrastructure (DOD 2004). Fundamental requirements are that the CBR protection for facilities is effective and reliable, i.e., whatever the strategy is, it needs to perform effectively when needed.

There is a need for a methodology to select the appropriate solution for a given Army building, occupancy, and function, and to develop the specification for the CBR protection system configuration. No adequate modeling and simulation capability to perform the necessary engineering studies and tradeoff analyses currently exists. There are significant deficiencies in the ability to computationally model and simulate the transient CBR contaminant dispersion inside a building during the critical first few minutes following an internal release. Real-time simulation and control of contaminant dispersion is needed for more sophisti-

cated CBR protection systems to predict the transient CBR transport following an event, to predict the effectiveness of various protective strategies, and to allow the containment of CBR agents.

Existing technologies that will enable DOD to fully implement its CBRNE protective policy must be identified and validated. Technology gaps in DOD's ability to respond to and resist specific CBR threats must be identified, and solutions that fill those gaps must be developed. This work summarizes past and current research in target technological areas, with a focus on three CBR protection sub-areas: (1) modeling and simulation of airborne chemical/biological contaminant dispersion in a building, (2) intelligent building control, and (3) CBR-related whole building diagnostics.

## Objectives

The objectives of this research are to identify existing technologies that will enable DOD to fully implement its CBRNE protective policy and technology gaps that will limit DOD's ability to resist specific CBR threats

## Approach

1. A comprehensive literature search was performed in three sub-areas of the CBRNE protection issue:
  - a. Modeling and simulation of airborne chemical/biological contaminants in buildings
  - b. Intelligent building control
  - c. CBR-related whole building diagnostics.
2. Data was compiled, reviewed, analyzed, and abstracted.
3. The annotated information was organized into subject-area and general bibliographies.
4. Conclusions and recommendations were drawn.

## Mode of Technology Transfer

It is anticipated that the results of this research will facilitate subsequent research into methods and technologies designed to protect Army facilities from airborne CBR threats.

## 2 CBR-Related Diagnostics

### Modeling and Simulation of Airborne Dispersion of Chemical/Biological Contaminants

The series of incidents related to the delivery through the U.S. mails of anthrax-laced letters in 2001-2002 illustrates two specific—and very serious—problems. First, the airborne dispersion of CBR contaminant within a building is very complicated. To develop safe building designs, successful protection measures, and effective evacuation plans, it would be critical to understand and model the dispersion profile within the first several minutes of contaminant release. Second, the major uncertainty in the de-contamination process is the lack of accurate information of the dispersion profile of cleaning agents through the air paths across the building. Without an accurate tool to generate detailed information of the dispersion profile of the cleaning agents, the time for de-contamination of the affected building is very slow; it took almost 2 years to decontaminate the Hart Senate Building.

Two priority problems that need immediate solutions are that:

1. Dynamic simulation of dispersion of CBR agents within a building under typical HVAC operation
2. Realistic definition of constitutive equations and boundary conditions to generate accurate dispersion profiles in a building (which is difficult to obtain through field experiments).

Simulation of airflow and contaminant transport in buildings can be classified under three categories, in increasing order of detail and complexity:

1. Box or single zone model
2. Multizone (MZ) or nodal model
3. Computational fluid dynamics (CFD).

Box or single zone models model the entire building as a box or single zone with airflow or contaminant transport through the building envelope. Such simple models do not provide detailed information about the airflow and contaminant transport within the building. MZ airflow models represent a building as a net-

work of discrete flow elements that connect at node. Such models have been used for some time in air circulation software to characterize building ventilation for the study of indoor air quality and energy conservation, and more recently for CBR contaminant transport. These models cannot provide concentration information as a function of time and space in a room, and they also have some inconsistencies with physical laws, e.g., instantaneous contaminant dispersions and uniform concentration.

“Computational fluid dynamics” is a broad term referring to the numerical solution of the equations that govern fluid flow, e.g., the Navier-Stokes equations, continuity equations, and any additional conservation equations for the specific application at hand, e.g., contaminant concentration or energy. Typical CFD software involves the iterative solution of equations balancing variables such as flow, mass, thermal energy (enthalpy), pressure, etc. for the particular physical phenomenon over a three-dimensional grid (or mesh) of volumetric cells that represent the particular geometry for the problem. CFD is a fully dynamic approach that can be used to develop detailed models of airflow and contaminant dispersion inside a building. CFD, however, also requires detailed input including realistic definition of the boundary conditions, and places major demands on computer speed and memory.

Computational modeling needs to be linked with the building system and control strategies to provide the CBR modeling and simulation capability needed to perform the necessary engineering studies and tradeoff analyses to select the appropriate solution for a given Army building, and to develop the specification for the CBR protection system configuration. A valid computational modeling capability will allow investigations to be done more cost effectively and more rapidly than experimental procedures involving the modification of infrastructure for an entire building.

## **Intelligent Building Control**

Current design, construction, and operating processes are inadequate to ensure a secure, reliable, and efficient facility that is also functional. The building automation systems (BAS) in most Army facilities were not designed to be secure. Almost no Army BAS were designed to protect or react to CBR events. Because of their advanced age and poor condition, these BAS are often unreliable or inefficient. A reliable and efficient BAS greatly increases a building’s ability to protect against CBR events. Buildings and their automation systems must be able

to detect CBR incidents, warn and protect personnel from such attacks, avoid any contamination, and respond appropriately to mitigate the impact of an attack.

One existing scheme, per UFC 4-010-01, calls for emergency shutdown of all air distribution equipment in a building. In many cases this “shelter-in-place” mode is a reasonable first level of response, but the DEPSECDEF memo requires an appropriate level of protection to provide mission continuity for mission critical systems. It further calls for simply providing protection or procedures necessary to safely survive CBR incidents, regardless of mission criticality. In both cases, simple shutdown of the air distribution systems may not be sufficient or appropriate. Immediate responses may instead call for zone or building pressurization, redistribution or redirection of air, activation of filtration systems and ultraviolet germicidal irradiation (UVGI) (Kowalski and Bahnfleth 2003), coordination with fire protection/life safety systems, and/or initiation of emergency response scenarios (emergency lighting, public announcement messages, notification of emergency personnel, etc.).

More effective and robust schemes than simply shutting off air distribution systems are possible, and some presently exist in rudimentary forms, such as zone isolation, zone pressurization, and building pressurization. Because buildings are not static entities, these schemes require investigation and modeling to identify their applicability and utility in CBR-specific applications. One example of the sensitivity of these schemes is that a change in the temperature of a zone of only 2 °F can result in the reversal of air flow direction. Moreover, commercially available building automation systems (BAS) and sensors from different manufacturers, do not ordinarily inter-communicate to share data and exchange commands because vendors often use proprietary communication protocols. Further complicating this situation is that cross-technology integration (e.g., HVAC BAS communicating with a life safety BAS) is not commonplace. Industry standard communication protocols are available, but the feasibility of multi-vendor cross-technology communication in the execution of CBR protective strategies and a method to accomplish that communication needs to be investigated.

## **Whole Building Diagnostics**

Computational modeling of CBR agent dispersion inside a building first requires realistic definitions of boundary conditions. As evident during execution of the full scale integrated system experimentation phase of the DARPA Immune

Building project, CBR agent transport and dispersion in buildings is highly dependant on the location and magnitude of unintentional air leakage sites, not only for the exterior building envelope, but also for internal zones (i.e., rooms).

Developing an accurate physical representation of the building's exterior and interior configuration, including unintentional air leakage, is just one part of establishing the required boundary conditions. Modeling of a room under actual HVAC operations also requires establishing parameters for representing the HVAC operating conditions (e.g., air supply and return devices, ventilation rates, system configuration such as duct/plenum return, airflows). The quality of the assumptions and estimations used to establish the parameters will determine the accuracy of the model.

To efficiently model CBR transport, it is also necessary to determine the scale of effects of building leakage on contaminant transfer and establish the level of leakage characterization required to adequately define the models. There is also the need to know when and how these parameters may change throughout the life of the building. Materials and components degrade over time and modifications and alterations to the building configuration are often made as the structure's use and occupancy change. Building diagnostic and measurement methods must be developed to obtain the necessary data.

Furthermore, any CBR protective strategies implemented in a building will be become part of the life-safety system of that building and must work correctly the first time and every time over the life of the building. Both initial commissioning at the end of construction and continuous commissioning over the operating life of the building will be necessary to ensure proper operation of the CBR protection system. This is a new requirement for HVAC and other building systems. Automated diagnostic techniques are needed to continuously assess the performance of the CBR protection systems over the life of the structure.

### 3 Modeling and Simulation of Dispersion of Chemical/Biological Contaminants

Emergency responses to a toxic industrial chemical (TIC) or chemical/biological (C/B) agent incident may vary greatly depending on the specifics of the agent release, e.g., whether the intrusion is internal or external, chemical or biological, and of short- or long-term duration. In each case of an attack, the most effective measures must be identified and implemented in advance through design and construction for a new building, retrofit reinforcement for existing buildings, and emergency response training exercise of the building occupants. The most effective measure in each scenario has not been well identified due to lack of experimental data. For example, conflicting recommendations may be given in the case of internal release of chemical or biological agents. A common recommendation on the HVAC system operation is “shut down all air-handling units until the type of hazard and extent of its spread can be determined” (ECBC and PDC 2001)

On the other hand, LBNL report 51959 recommends a number of approaches different from “just shutting off the air-handling units” (Price et al. 2003). Field experimentations of these approaches are time and cost prohibitive. An accurate simulation of each scenario on a high performance computer provides a cost effective method to evaluate the protective measures. In the modeling and simulation of TIC or CBR incidents, three categories of simulation software are currently available in the private and public sectors. These are categorized into the environmental regulatory models, the real-time dispersion-deposition-casualty models, and the building indoor dispersion models.

#### Environmental Regulatory Models

Many environmental regulatory models are available. Approximately seven preferred models are preferred:

- AERMOD Ver. 2222 BETA, from AMS/EPA:  
<http://www.epa.gov/scram001/tt26.htm>

- ISC3 (Industrial Source Complex Model), from Pacific Environmental Services (EPA funded):  
<http://www.epa.gov/scram001/tt22.htm#rec>
- BLP (Buoyant Line Point Source Model), from Environmental Research Technologies:  
<http://www.epa.gov/scram001/tt22.htm#rec>
- CALINE3, from California Department of Transportation:  
<http://www.epa.gov/scram001/tt22.htm#rec>
- CALPUFF, from Earth Tech:  
<http://www.epa.gov/scram001/tt22.htm#rec>
- CTDMPLUS (Complex Terrain Dispersion Model), from National Technical Information Service (NTIS) :  
<http://www.epa.gov/scram001/tt22.htm#rec>
- OCD (Offshore and Coastal Dispersion Model), from Donald DiCristofaro (U.S. Department of Interior funded) :  
<http://www.epa.gov/scram001/tt22.htm>

Slight variations exist among these models, but all are generally based on statistical Gaussian plume numerical engines. They are capable of determining contaminant concentrations within the air, and upon deposition. Most do not incorporate aerodynamic effects of buildings and terrain. The latest preferred model listed by the EPA is AERMOD, which is considered the most accurate regulatory model available. AERMOD is an improvement over Industrial Source Complex (ISC3) with increased accuracy of terrain depiction, vertical and horizontal turbulence modeling, atmospheric convective mixing, and inclusion of building aerodynamic effects. The model sizes considered with these programs range from the regional scale (100 km) to the site scale (1 km). Typical grid resolution is approximately 1 m. These models are not suitable for modeling building indoor air conditions.

## Real-Time Dispersion-Deposition-Causality Models

The models listed in this category are designed to be used by emergency managers, warfighters, and scientists to limit the loss of life in actual chemical release scenarios:

- HPAC (Hazard Prediction and Assessment Capability), from Defense Threat Reduction Agency (DTRA) :  
[http://www.dtra.mil/td/acecenter/td\\_hpac.html](http://www.dtra.mil/td/acecenter/td_hpac.html)
- NARAC (The National Atmospheric Release Advisory Center), from Lawrence Livermore National Laboratory:  
<http://narac.llnl.gov>
- READY (Real-time Environmental Applications and Display System), from NOAA Air Resources Laboratory:  
<http://www.arl.noaa.gov/ready.html>

These models link real-time weather data, topographical data, dispersion modeling, and population data in one program. They provide human dosage levels at areas of interest within the model. The numerical engines for the contaminant dispersion portions of these programs are based on statistical dispersion methods rather than the fundamental equations of fluid flow. HPAC and NARAC use different mathematical and numerical solutions (USDТА 2002). HPAC uses a second-order closure equation and a Gaussian puff method, while NARAC uses the diffusion equations and a Lagrangian-Monte Carlo particle method. Computational time for these models is designed to be brief to enable users to make decisions regarding human health as quickly as possible after the release. The government has extensively tested both of these models, and they are considered the best tools for their intended use. The model sizes considered with these programs range from the regional scale (100 km) to the site scale (1 km). A paper comparing HPAC and NARAC considered a 10 m grid cell to be fine resolution, and a 40 m grid cell to be coarse resolution (Nasstrom et al. 2002). These models are also not suitable for modeling building indoor air conditions.

## Building Indoors Dispersion Models

Traditionally multizone models have been used for airflow calculations related to the building indoor air quality (IAQ) problems. In the multizone models, a building is represented as a network of well-mixed spaces, or zones, connected by discrete flow paths such as doors, windows, wall cracks, fans, ducts, hallways, and so on. The model predicts the system's behavior based on the interaction of the assembled components and the conservation of mass. The two most popular multizone models are:

- COMIS, developed by the Lawrence Berkeley National Laboratory (LBNL). LBNL's Airflow and Pollutant Transport Group continues to develop and use

this model:

[http://eetd.lbl.gov/IED/APT/APT\\_tCFD.html](http://eetd.lbl.gov/IED/APT/APT_tCFD.html)

- CONTAM 2.1, is a product of the National Institute of Standards and Technology (NIST) :

[http://www.bfrl.nist.gov/IAQanalysis/docs/NISTIR\\_7049.pdf](http://www.bfrl.nist.gov/IAQanalysis/docs/NISTIR_7049.pdf)

Both programs have similar capabilities and similar shortcomings. Assumption of uniform concentration and instantaneous dispersion in a room would be reasonable for IAQ problems, where accurate description of air and contaminant flows in a room is not of particular concern. However, in case of CBR attack inside a building, dynamic dispersion of an agent for the first several minutes (say for the first 15 minutes) is critical information for emergency measures such as evacuation, activation of containment, purge, and de-contamination. The assumptions of uniform dispersion in the multizone models fail to provide dynamic agent concentration in a room. These limitations should be addressed in studies either through integration of the computational fluid dynamics (CFD) models with the multizone models, or through full-scale CFD modeling of a whole building (Mora et al. 2003). High performance super-computing may facilitate such extensive numerical calculations associated with the numerical simulation of a whole building.

## Challenges in Building Indoors Dispersion CFD Simulation

CFD modeling of airflow and contaminant transport inside a whole building is an extremely challenging, if not impossible task. The expected challenges include required computational resources to accommodate extensive calculations involving a large number of grid cells (that should contain meaningful physical information), realistic definition of complicated boundary conditions involving the details of the physical objects/configuration and interactions, and realistic HVAC operation and associated software engineering to make the numerical calculations doable. The CFD modeling of contaminant dispersion within a building requires realistic definition of boundary conditions for each room and leakage between them as well as interaction with the building envelope and with the external environment (Liu and Nazaroff 2001). Note that 10-air changes per hour through a building envelope is rather typical for a moderately pressurized building space (Persily 1999). Realistic definition of boundary conditions along the building envelope is needed for an accurate simulation of internal dispersion infiltrated through the building envelope (Knight et al. 2002). The airflow inside a building is complex phenomena governed by various modes of HVAC control

(heating, ventilating and air conditioning), associated airflow control equipment (fans, dampers, ducts and diffusers), physical parameters (temperature, humidity, and contaminant concentration), and physical configuration of objects in a building (Federspiel et al. 2002, Sippola and Nazaroff 2004).

The airflow in a building is inherently non-linear in mathematical terms. Note that a small change of pressure in one room (e.g., action request by room thermostat) will result in change in supply and air flow in general. That will, in return, affect the physical state of the room. For a typical building, there are a large number of rooms and defined spaces. Definition of a reasonable set of boundary conditions to each space and room is a challenging task. A CFD simulation of dispersion inside an apartment building has been attempted with limited success (Cybyk et al. 1999). The major cause of potential error was attributed to the large leaks in the attic, i.e., not well-defined boundary conditions. Since a typical building has a large number of rooms and spaces, a CFD simulation of airflow and contaminant dispersion room-by-room and space-by-space approach will require amounts of computational resources large enough to challenge even ultra modern supercomputers when carried to high resolution (with grid size of a few inches).

## Summary

Modeling and simulation of dispersion of pollutant for the purpose of control of air pollution has been well established. There are a number of “Environmental Regulatory Models” that could be applicable for simulation of dispersion of CBR agents over a wide region. Typical grid resolution is in the order of 1 km, which is too coarse to describe CBR agent concentration profile around a given building.

Another group of model is “Real-Time Dispersion-Deposition-Casualty” models. These models are developed to assist first responder activities. They link real-time weather data, topographical data, dispersion modeling, and population data in one program. The domain of these models is also a wide region, with typical grid scale in the order of 1 km. These models are not suitable for modeling accurate concentration of CBR agents around a building and/or concentration inside a building.

The contaminant dispersion inside a building has been a traditional subject of indoor air quality (IAQ) studies. For IAQ applications, accurate calculation of

concentration level of contaminants is not of critical importance. For CBR protection, however, accurate determination of the concentration level is directly related to the life-or-death issues. An example would be filtering of contaminants through HEPA filter (which provides 99.97 percent filtration efficiency). The HEPA filter will sufficiently meet the IAQ needs. However, filtering 1 billion anthrax spores through a HEPA filter will still allow 0.3 million spores to pass into the building, resulting in mass casualty inside a building.

The multizone model has been successfully applied for IAQ studies inside a building during the past years. Due to its simplistic physical assumption (of homogeneous and instantaneous dispersion of contaminants in a given zone, i.e., room, hallway, etc), the multizone model cannot provide the desired level of resolution required in the CBR protection. Computational Fluid Mechanics (CFD) based modeling and simulation has started recently, especially since September 2001, to accommodate the need of simulation of CBR agent dispersion inside a building. CFD modeling of concentration profile around a building envelope, realistic modeling of complex physical configuration inside a building, and modeling of HVAC components and operation are the challenging tasks under active study currently.

## 4 Intelligent Building Control

### Introduction to Building Automation Systems

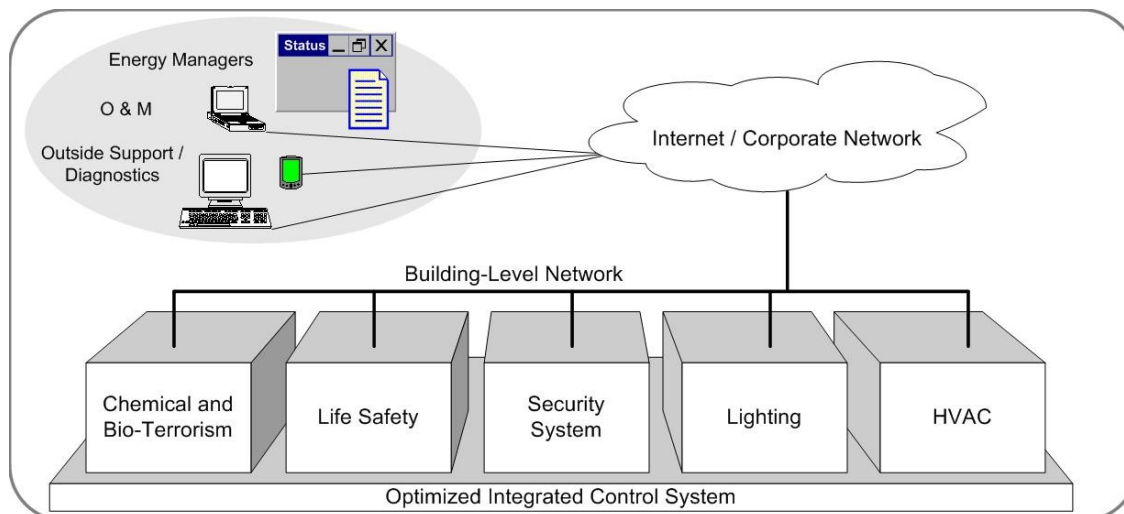
A building automation system (BAS) can be defined as a collection of components consisting of input and output devices (such as sensors and actuators) that are used to perform tasks based on control logic, where the control logic is coded (or programmed) into a microprocessor-based device. The building automation systems in a typical building are used to control the various mechanical and electrical systems that usually consist of: HVAC, security/access, and life safety systems (fire and smoke control). Additionally, in more modern buildings other BAS subsystems might be used to monitor and control: communications systems, fuel systems, lighting, backup generators, uninterruptible power supplies, public address systems, elevators, and escalators.

### Intelligent Building Control

Intelligent building control can be defined as the holistic and integrated use of a building's automation systems to perform self-optimizing tasks based on logic and reasoning. Much like the human body, the various building BAS subsystems must operate in coordinated and efficient manner. All subsystems must communicate and share data, and be capable of processing the data to make effective decisions (Figure 1). If a given subsystem is not functioning properly, other subsystems must respond accordingly.

### Intelligent Building Control CBR Needs & Capabilities – Where Are We?

Most Army facilities were not designed to provide CBR protection. This includes the building automation systems. Historically the integration of BAS and life safety systems has been constrained to fire and smoke control where the life safety system is used to automatically shutdown the HVAC system or by placing it under manual control by fire department personnel, but a more holistic approach is being considered by many in the BAS industry.



**Figure 1. Intelligent building control.**

The following excerpts from various publications give a sense of where the BAS industry is headed:

To accommodate planned responses to emergency events, buildings need to contain reliable and redundant communication systems that can be used to inform building occupants of what is happening and instruct them as to what to do. Life-safety systems and HVAC-system controls must work together to minimize the danger to building occupants and allow them the opportunity to escape. For instance, fire alarms need to be interfaced with HVAC controls to shut down systems or place them in a smoke-control or a purge mode. Also, life-safety systems need to provide the data necessary for building operators to make correct decisions regarding how to handle the emergency at hand using prepared plans. These systems need to be tested during their commissioning and regularly during their normal maintenance cycles to verify that they will operate as intended if the need arises (Cosiol 2002).

While there are prescriptive code requirements that generally address these (life safety and CBE event) situations, there is little consideration for new technologies that have yet to be written into the code, but that may provide a superior solution. While dealing with terrorist threats and attacks is clearly not within the scope of traditional building code and life safety documents, many buildings may be susceptible (as direct targets or by proximity to direct targets) and more are being designed, thus this subject needs to be addressed. Unfortunately, the building and life safety codes have no means for dealing with the impact of these types of sys-

tems; therefore implementation of effective security and CBR measures can be frustrating and self-defeating (Jaeger 2002).

There are many reasons for integrating fire alarm systems with other building automation and control systems. Examples include smoke control, single-seat access to building information, easier maintenance, sharing sensor data, obtaining information about the location of people during an emergency, and providing infrastructure for new technology to improve performance and safety. ... What is needed is a way for the fire alarm system to command the HVAC control system to enter a smoke control mode and let the HVAC controllers manage the equipment (Bushby 2001).

## Professional Societies and Other Organizations

Several professional societies have addressed intelligent building control in relation to protective strategies. Presented here is a summary of those relevant societies, and the direction in which they are working:

ASHRAE—The American Society of Heating, Refrigerating, and Air Conditioning Engineers published a report *Risk Management Guidance for Health, Safety, and Environmental Security under Extraordinary Incidents* that concludes that ‘Integrating the control sequences of HVAC systems for normal and extraordinary periods of operation is a critical design issue.’ It further recommends that ‘Unless building-specific guidance is provided to the contrary it is recommended that activation of fire protection and life safety systems and implementation of automated fire safety strategies be placed at a higher priority than possibly-conflicting automated strategies designed to respond to other extraordinary conditions’ (ASHRAE 2003). ASHRAE also has an Ad Hoc Committee on Homeland Security which is investigating development of possible ASHRAE standards and guidelines that would support the ASHRAE homeland security efforts.

CABA—The Continental Automated Buildings Association published a report ‘Technology Roadmap for Intelligent Buildings’ that provides an in-depth examination of intelligent buildings technologies. It focuses on the current status and opportunities offered by use of intelligent building technologies. It specifically addresses the integration of various building systems including the need to integrate life safety systems with the other BAS functions. The report states that ‘Life safety systems, notably fire

systems, are heavily regulated by stringent code requirements. These requirements do not, however, prevent the information originating with a fire safety system from being provided to any other systems' (Continental Automated Buildings Association, 2002).

## Active BAS Schemes in Response to CBR Event

One existing CBR life safety scheme calls for emergency shutdown of all air distribution equipment in a building (UFC 4-010-01). An additional level of protection can be provided by closing bubble-tight dampers (ETL 1110-3-498). In many cases these "shelter-in-place" actions are a reasonable first level of response, but the DEPSECDEF memo requires an appropriate level of protection to provide mission continuity for mission critical systems. It further calls for simply providing protection or procedures necessary to safely survive CBR incidents (regardless of mission criticality). In both cases, simple shutdown of the air distribution systems may not be sufficient or appropriate. Immediate responses may instead call for zone or building pressurization, redistribution or redirection of air, activation of filtration systems, coordination with fire protection/life safety systems, and/or initiation of emergency response scenarios (emergency lighting, public announcement messages, notification of emergency personnel, etc.).

Manipulating the HVAC system can help slow the spread of a chemical or biological agent, or can rapidly clear a chemical agent out of a building, and that rapid response can save lives. Lawrence Berkley National Laboratory (LBNL) further indicates that, in the event of an internal chemical release, it is best to leave the HVAC system operating without alteration and that some HVAC manipulations can be beneficial. Under normal operation, a properly operating HVAC system will provide some outdoor air and will exhaust some indoor air, so it will help dilute the chemical and exhaust it from the building. For most buildings the normal operation of the HVAC system will tend to isolate areas that are served by different air handling units, thus helping to slow the spread of contamination. The isolation is reduced if the HVAC system is not properly balanced, or if the building's air recirculation system mixes air from different supply zones. Additional actions are possible including:

- pressurizing stairwells with 100 percent outdoor air—this will help provide a safe evacuation route
- putting the air handlers that serve heavily contaminated areas onto full exhaust and shut off supply to those areas—this will force air to flow from safe areas to contaminated areas, rather than the other way around

- provide 100 percent outdoor air to uncontaminated areas and areas with people in them—this will help keep people safe, as long as the chemical isn't being released into those areas' air intakes

LBNL also indicates that depending on the HVAC design, some of the items above may be performed by putting the building into a "smoke removal" mode.

A draft report that describes tactics and schemes for dealing with CBR attacks (Felker 2004) suggests the need for CBR-resistant building design including giving fore-thought to the building architecture (including HVAC zoning) such that it pairs up with the building automation system to provide for optimized CBR resistance. The use and control of smoke or isolation dampers plays a key role, along with the definition of smoke control zones and sandwich pressurization systems (pressurized zones or floors in multi-storied buildings). The report lists other architecture considerations and design analysis issues. It further suggests basic operational modes: shelter-in-place, zone isolation, and zone pressurization. For existing buildings, similar schemes can be employed to a lesser extent using existing fire and smoke control schemes.

The foregoing discussion focused on noncritical facilities. The U.S. Army Corps of Engineers Protective Design Center developed ETL 1110-3-498, *Design Of Collective Protection Shelters To Resist Chemical, Biological, and Radiological (CBR) Agents*. This document provides HVAC system guidance that seems to be primarily focused on mission critical facilities. It defines collective protection strategies to provide a toxic-free area where personnel can function without individual protective equipment. Of interest are the "protection" and "facility" classifications:

- Collective Protection Class I, II, III describe building capabilities ranging from passive protection (Class III), sometimes referred to as "shelter in place," to pressurization with filtration (Class I)
- Facility Classifications IA, IB, IC, and ID pertain to existing facilities, and describe their potential for supporting a collective protection system based on the buildings' pressurization capabilities

These classifications help to define system-types around which a building automation system could be designed. While ETL 1110-3-498 seems to be primarily geared towards mission critical systems, at least portions seem applicable to non-critical facilities, particularly where the threat level is high. Implementation cost might be a factor.

## Intelligent Building Control — CBR BAS Control System Requirements and Challenges

The design and use of the BAS to provide an intelligent and automated response in the event of CBR attack requires consideration of several issues, parameters, and application requirements:

- *Control Hardware Reliability and Quality of Performance.* System design must meet life safety code (such as NFPA) requirements. Critical control components such as those that are controlled by the HVAC control system to provide CBR protection must be high quality and minimally meet Underwriters Laboratory (UL) listing requirements. Availability and effectiveness of sensors is at issue. Biological sensors that can detect in real-time do not exist. A maximum 15-minute delay (per ETL 1110-3-498) from the initial presence to a possible positive report is required, however, “current biological detection technology requires a minimum delay of approximately 30 minutes to detect the presence of biological agents” (Finkelstein 2001). Chemical sensor accuracy and cost may be an issue. Pressure and airflow sensor accuracy/drift/location might be an issue. Additional quality assurance might be accomplished by using the BAS as a quality assurance tool where it continuously verifies proper performance of the BAS.
- *Integration and Interoperability.* All BAS and life safety systems must be integrated, most notably the HVAC BAS. This might include use of a standard network communications protocol to provide for sharing of data between different vendors’ hardware, sensors, and systems. This is particularly important where multiple suppliers/vendors provide BAS control hardware such as in open-bid situations and where systems are expanded over time.
- *Network Reliability and Quality-of-Performance.* A reliable and properly functioning network is important. Proper network design and construction quality verification will be important. One key network architecture feature that may be required is the use of network hardware, such as a router, to filter and provide isolation of any interconnected life safety BAS. Redundant communication pathways and methods (such as wireless) will likely be a partial solution to providing reliable networks. Isolation hardware protects the life safety BAS from failure or malfunction of the control network or other BAS systems.
- *BAS Control Functionality.* The BAS control algorithm(s) must be robust and designed to provide the needed and desired functionality. This is discussed in the next section.

In summary, tentative requirements of a CBR-protective intelligent control system might include:

- The BAS must operate on a defined hierarchy where the fire and smoke control systems have first priority over equipment operation. For example, if the fire/smoke control system wants to turn off an air handler, then it has priority over any other BAS command.
- Where life safety systems (such as fire and smoke control panels) communicate with other BAS systems such as the HVAC controls, the individual systems should be isolated using common control network hardware such as routers. This protects the life safety system from failure or malfunction of the control network or other BAS systems.
- Critical control components such as those that would be controlled by the HVAC control system to provide CBR protection must be high quality and in at least some cases minimally meet Underwriters Laboratory (UL) listing requirements.

## **Intelligent Building Control — CBR BAS Control System Algorithms**

The initial design and subsequent use of a BAS algorithm to provide an automated response in the event of CBR attack requires consideration of several issues, parameters, and application requirements:

- type of release (C, B, R)
- quantity of release
- location of release (internal/external)
- time of release
- confidence level of type, quantity, location, and time of release
- building characteristics. (Number of floors, zoning, pressure class, number of HVAC systems, HVAC system type, specific HVAC equipment, CBR protective features and equipment, etc.)
- ability of control system to recognize equipment malfunctions and sensor inaccuracy
- thermal, energy, and mass balances.

The potential complexity of a control system model and algorithm suggests the need for simplifying the control system design process. Accuracy of the model/algorithm is also likely to be key to its performance. One possible approach is to link the architectural, mechanical, and electrical (A/M/E) design to design of the BAS design. Corps of Engineers design drawings are usually based on CADD standard 2.0. This provides one element of a standard approach for

integrating building design with the BAS design. Other existing standards and tools should also be considered as part of the design process.

Possible control algorithms may vary from simple to complex. It may involve the use of a simple if-then scheme with resultant on-off, open-closed command outputs, or it may require more complex or advanced control. An example of an advanced/intelligent control objective would be to predict and control building and/or zone pressurization, inter-zonal airflows, and/or ventilation flows based on control damper and supply/return/exhaust fan manipulation.

Various BAS-implemented advanced control algorithms and models might be used to perform intelligent building control, including a self-optimizing feature that continuously learns or adapts and that can potentially provide feedback to verify proper system performance.

## **Simulation, Modeling, and Control Algorithms**

### ***Machine Learner***

One advanced control algorithm possibility is referred to as a “Machine Learner” (Chang 1999). The idea is to use a Machine Learner, for example a neural network in conjunction with analytical simulation to reduce the computational time of simulations. There are at least three uses for simulations: Sensitivity Analysis, Goal Seeking, and What-if analysis. Machine learning techniques vary. Some encountered in this literature search were: supervised, reinforced, and unsupervised. Machine Learning is useful for the following (paraphrased from Chang 1999):

Control that is theoretically definable but too complex, processes that have poor transient response, stabilization of process needed for efficient operation at several equilibrium points, and when a control should be carried out on the basis of output patterns and the state space is partitioned into disjoint regions that are equivalent for purposes of control, therefore, the optimal input corresponding to each region is required.

### ***Bayes Monte Carlo Updating***

Sohn, Reynolds, Singh, and Gadgil present the exploitation of a feature of this technique that was previously unused. The feature is described as the ability to decouple modeling and data analysis. This is important because other tech-

niques are too slow to be applied for online, real-time sensor data interpretation (Sohn et al. 2002).

## Summary

- The vast majority of Army facilities were not designed to provide CBR protection. Those that do generally only include critical facilities and usually only provide for filtration of CB agents.
- Existing life safety systems (such as fire and smoke control systems) provide some elements and capabilities that can be used to provide CBR protection including system shutdown and a building purge mode.
- The design of BAS and Life Safety Systems must be coordinated to provide CBR protection. This coordination is not presently the norm, but should be factored into the design process.
- The BAS can provide an increased level of protection through its capability to monitor the building's CBR sensors, pressures, flows, equipment on/off status and through its ability to shutdown systems, turn on/off fans, pressurize spaces/zones, and control air flow.
- Investigation into using a Machine Learner in conjunction with simulation techniques for evaluation of building controls such as temperature and air-flow should be pursued.
- Architectural design aspects of the building such as its facility (pressurization) class and zoning must be coordinated with the BAS design in order to maximize the capability of the BAS to provide CBR protection.
- While the BAS can turn equipment on/off, pressurize spaces, and control air-flows, the optimal relationship between the various CBR prevention and response techniques (ventilation, filtration, and irradiation) is not known and should be further investigated.
- The BAS can facilitate access to timely, comprehensive, and accurate data and information. This data can be made available to the building operator and "first response teams" through the local network and through external data transmission over high speed networks.
- Currently available biological sensors are inadequate in terms of the agents they can detect, detection time delay, reliability, and affordability.

## 5 CBR-Related Whole Building Diagnostics

### Building Envelope Performance/Air Leakage

Building air leakage can be defined as the unintentional flow of air in and out of a building through leakage paths in the building envelope as well as the airflow between interior building zones. It is dependent on the size and distribution of air leakage sites, pressure differences caused by wind, temperature, equipment effects (i.e., vented combustion equipment, exhaust fans) and HVAC system operation. Improving indoor air quality, reducing energy usage, and eliminating damage due to moisture accumulation have been the primary impetus for building leakage studies (ASHRAE 2001; Colliver 1994). Research for quantifying air leakage and determining the sources of leaks has been conducted for the particular purpose of determining the impact on these issues. Air leakage tests are commonly performed on all types of buildings to identify potential retrofit measures and understand where improvements in design and construction techniques can reduce overall building air leakage to reach desired acceptable levels (Persily 1993).

The most often used air leakage measurement technique is the fan pressurization test, which can be used to determine air infiltration characterization for whole buildings, multiple zones of buildings, and individual construction components. The more sophisticated tracer gas techniques are also used to measure airflow between building zones and through the envelope. Methods such as infrared thermography, smoke and acoustics are diagnostic tools that are means for identifying leak source locations, but not measuring the amount of air leakage.

### Whole Building (Single Zone) Fan Pressurization

Fan Pressurization is a simple and well-developed technique for measuring the overall airtightness of single zone building envelopes. Single zone buildings are

those that have essentially zero pressure difference between any two parts of the interior volume of the deliberately conditioned space. This technique involves setting up a mechanical air moving device such as a large fan into an exterior opening of the building. The air leakage is quantified by creating pressure differentials between the building interior and outside environment incrementally; and measuring the resulting controlled airflows required to achieve steady state conditions. These whole building fan pressurization tests can be used to determine an overall effective leakage area (ELA) at a particular pressure differential, compare the leakage rates of different buildings and determine the reduction in air leakage of a building envelope due to incrementally applied retrofit measures.

The ASTM E 779 *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization* provides a method for determining the air leakage on single zone buildings. Multi-zone buildings can be treated as single zone buildings by achieving equal pressurization throughout the building via the opening of doors and/or use of fans. A fan or blower, which can provide constant measurable airflow at the selected pressure differences, is typically employed to achieve pressurization and depressurization. This airflow through the fan is assumed to be the same as the airflow through the test zone (i.e., building envelope). Pressure difference ( $\Delta P$ ) and flow ( $Q$ ) data are taken at increments of 5 to 10 Pa to establish a correlation between the two and calculate the leakage coefficient ( $C$ ) and pressure exponent ( $n$ ) for the airflow power law equation ( $Q = C\Delta P^n$ ). The ELA at the reference pressure of 4 Pa is also usually calculated. The ASTM standard also provides calculation methods for determining the confidence limits for the derived values. The uncertainties associated with these tests have been studied by several (Persily 1983; Sherman 1995).

For homes and small to medium size buildings, the blower door test method can provide the necessary pressurization. The setup includes a large fan placed in a doorway, with the remaining portion of the opening sealed with an airtight fabric and supporting frame. There is an abundance of data of building air leakage derived from these standard blower door tests (Sherman 1998). For buildings where greater airflows are necessary, a larger fan unit or blower that may require an opening larger than a standard doorway can be used (Shaw 1990).

Envelope air leakage tests can be accomplished on large buildings, where airflows are much greater than can be practically supplied by temporary equipment, by using the in-place air-handling units to provide the differential pressurization. The procedures for using the “building air handling system” method

are described in Report CAN/CGSB-149.15-96. Bahnfleth et al. (1999) established preliminary criteria for conducting envelope air leakage tests using this method and proposed some general guidelines based on field investigations. Using the building's air handling system could potentially provide a means of monitoring envelope air leakage on a regular basis throughout the life of the building. Through simulation, they showed that an uncertainty of 3 percent for the estimate of air leakage flow rate at 50 Pa could be achieved.

## **Multizone Building Fan Pressurization**

There have been research studies performed and test methods developed (Modera 1990) to characterize air leakage between internal zones in multizone buildings as well as the exterior walls of zones. A common characteristic of these methods, which are often referred to as "balanced fan methods," is the use of zero pressure differences between the zones of interest and adjacent zones for the purpose of ensuring that no leakage occurs between the two. This is typically achieved by employing additional fans. Furbringer and Roulet (Furbringer 1991) describe two common approaches to the multifan pressurization technique and provide a study of the errors and confidence intervals of the results generated by each. For one approach, the control of the zero pressure difference was found to be the instrumental source of error; and for the other, the accuracy of the airflow measurements was more critical. For both approaches, the confidence intervals are of the same order of magnitude as the results themselves.

When performing multifan pressurization tests to separate exterior envelope leakage and interior partition leakage components on larger buildings, very large fans may be required to achieve the zero-pressure differential with adjacent zones. To address this, Proskiw and Parekh (2001) have proposed comparatively simpler and less expensive means for separating these leakages by not requiring exact equalization, but only modification of the partition pressure differentials through use of a second fan. To gain insight into the functionality of the new test procedure under field conditions, a series of trials were carried out on two buildings. Initial field test results have been mixed but encouraging.

## **Building Component Fan Pressurization**

Some of the major sources of building air leakage are joints where materials and assemblies connect and at envelope penetrations. Fan pressurization methods

have been developed for measuring air leakage on specific parts of the building shell. These include laboratory tests that provide the capability of evaluating particular component products and design/construction details and in-situ field tests that serve as diagnostic tools for determining how leaks are distributed throughout a building. With the motivation for these tests being primarily energy conservation and building ventilation related, their focus has been on exterior component leakage and not the leakage of components of interior partitions.

ASTM E 283 provides a standard laboratory procedure for determining air leakage of exterior windows, curtain walls and doors under pressures applied across a sample. The test consists of sealing the component test specimen against an air chamber and measuring the airflow through it at a specified pressure differential (i.e., 75 Pa). The airtightness of the component, as manufactured, is measured. The precision and bias for the method are not provided within the standard. However, it should be noted that a 5 percent error for the airflow rate is allowed. An ASTM E783 test method, which uses these same principles, can be used to evaluate doors and windows under installed conditions but does not include the air leakage between the assembly and the adjacent wall construction.

Shaw (1980) developed and validated methods for conducting small-scale pressurization tests to measure air leakage through entire wall assemblies and their individual components in the field. A typical setup involves sealing an airtight chamber made of plywood panels covered with plastic sheeting around the perimeter of the test area and pressurizing the chamber in a controlled manner using a portable fan. As with other fan pressurization methods, the flow rates into or out of the chamber are measured at several pressure differentials to establish the airflow power law equation. The balancing of pressures across adjacent zones and rooms using additional fans is critical for eliminating undesired extraneous air leakage. In this particular study, air leakage rate was measured for the exterior wall of an apartment unit. Additional tests using different chamber setups were performed to measure the leakage rate for a window, windowsill and the floor wall joint using two different methods. The direct method was very similar to that used for the wall with modifications required for the test chamber and pressure balancing. The indirect method, sometimes call the “selective pressure sealing method,” uses the setup that is employed in the direct method except that the component being measured is sealed. This can be done for one component or for several components tested in succession. The difference in leakage before and after masking the component makes up the air leakage flow of the component. Colliver et al. (Colliver 1994) noted that thorough analysis of errors involved in using this technique has not been completed. They suggest

potential problems being that: (1) the total errors in accuracy for the overall air-flow readings before sealing may be so large that they make the errors in the differential readings quite large, and (2) there is evidence from previous testing that some hysteresis in the sealing order occurs. The order in which components are sealed make a difference in the calculated leakages for the components.

## Tracer Gas Dilution

Unlike fan pressurization tests that rely on inducing pressure differentials during testing, tracer gas dilution tests provide a means of determining building air-flow under ambient conditions. The ASTM E 741 test method describes the technique for determining a single zone's air change with the outdoors, as induced by mechanical ventilation and wind and temperature effects. The test method assumes that the tracer gas concentration in the test zone is the same throughout. The standard discusses procedures for preparing the test zone; procedures and equipment for distributing, sampling and analyzing the tracer gas; and methodology for performing analyses of errors.

Three techniques are described in the standard: (1) concentration decay, (2) constant injection, and (3) constant concentration. The three procedures require different injection and air sampling strategies and therefore equipment of varying complexity. These must be considered along with their comparative capabilities when selecting a particular technique for an intended purpose.

The concentration decay method involves introducing a small amount of tracer gas into the test zone and mixing to achieve uniform concentration. Air samples are taken at specific time intervals and the their tracer gas concentrations are measured to determine the average air change rate. This method is the simplest to perform in terms of required equipment and setup and is particular useful for getting a quick one time average air change measurement. However, a single decay test cannot provide continuous measurement of varying air change rates.

For the constant injection method, a tracer gas is injected into the test zone at a constant rate. The tracer gas concentration is measured at specific time intervals and used with the tracer gas flow rate to determine average air change flow. With this method, on-site sampling analysis has an advantage over off-site analysis because the concentration equilibrium can be assured during the test. If off-site analysis shows that equilibrium is not met, the test must be re-run.

Like the decay test, this method is not very useful for measuring air change rates in zones incurring unsteady ventilation/leakage.

The constant concentration method requires the most complex setup and sophisticated equipment. The tracer gas concentration in the zone is held at a constant level through continuous tracer gas injection using automated equipment and a feedback loop. The equipment monitors the concentration and controls and meters the injection rate. Zones with varying ventilation rates can be investigated using this method.

In a literature review of techniques for measuring airflow within buildings published by Lawrence Berkeley National Laboratories, McWilliams (2002) discusses research studies related to tracer gas measurement techniques. These particular studies included passive sampling techniques, tracer gas comparisons, and comparisons of different test methods and their associated error analyses. Investigations that employed tracer gas techniques for measuring outdoor infiltration for multizone buildings were also discussed. These typically used some variance of the constant concentration method and a single or multiple tracer gases simultaneously.

The values of the air change or airflow determined using tracer gas decay test methods apply to the specific weather and mechanical ventilation conditions prevailing at the time of the test. These values will change for the same building as wind and temperature changes or the operation status of the HVAC system is adjusted. Relating the building airflow to specific conditions requires running the tracer gas tests at those conditions. This is unlike fan pressurization tests that measure flow parameters and airflow as a function of pressure ( $Q = C\Delta p^n$ ), thereby permitting the modeling of natural air change due to wind and pressure changes.

## Air Leakage Site Detection Techniques

Three principal techniques for locating air leakage sites in building envelopes are: (1) infrared scanning, (2) smoke tracer, (3) and sound. The first two are often performed in conjunction with building depressurization (or pressurization) to provide a driving force for the airflow through leakage sites. ASTM E 1186 provides guidelines and procedures for employing the different techniques and describes the advantages and limitations of each. They can be used to assess

and evaluate the effectiveness of retrofit measures, but do not provide the capability of performing measurements of airflow.

Infrared (IR) thermography has been widely used in building diagnostics applications (Balaras 2002). It is a technique for visually representing small temperature differences on a radiating surface. Inspectors can determine locations of air leakage through the building envelope when exterior and interior temperatures are different. IR also has the capability of detecting leaks in HVAC ducts. With advancement in IR imaging equipment, there has been recent investigation into extending their use, when combined with suitable processing algorithms for interpretation, to provide quantitative measurements for assessing building defects (Grinzato et al. 1998). Grinzato discusses an interesting technique of integrating infrared thermography with fan pressurization tests. A differential IR image is produced allowing air leaks on interior wall surfaces to be distinguish clearly from thermal bridging.

The smoke test involves filling a building or room up with smoke and determining where the smoke passes through the partition or building envelope. The test can be conducted using the natural driving forces on the building, but it works better when the zone is under pressurization.

The “acoustic leak location method” described by Keast and Pei (1979) used a sound-making device on one side of the building envelope and a portable sound detector controlled by an operator on the other side. The operator moves the detector along the envelope very close to the surface and surveys for an increased signal, which indicates a leak location. Simple household equipment can be used for the both the sound source and the detector. McWilliams (2002) cites experiments conducted by Oldham et al. (1991, cited in McWilliams, p 57) that used an acoustic technique to attempt to determine crack sizes in buildings. The experiments were conducted in a laboratory environment using a wall made of steel beams. Although the technique worked well under these conditions, McWilliams’ review of the literature printed since those tests indicate it does not show promise in the building science field.

Some exploratory research (Peiponen 1989) has investigated the potential for using holographic interferometry utilizing a pulse laser for visualizing leakage flow. As with the acoustic technique, the literature search found no real advancement in application of this technique for characterizing building air leakage.

## HVAC Diagnostics

Successfully implementing airborne CBR protective strategies in Army buildings will require the use of automated HVAC diagnostic systems that presently do not exist. These automated HVAC diagnostic systems are needed to provide modeling and simulation boundary conditions for building HVAC systems (air flow-rates, damper positions, CBR sensor status, etc) so that appropriate airborne CBR protective systems can be designed and operated (in real-time) in Army buildings and to facilitate the initial and continual commissioning of CBR protective systems to ensure the proper operation of these life safety systems over a facility's life cycle.

HVAC diagnostic systems can be used to automatically identify problems with the operation of HVAC components in real-time:

A range of diagnostic systems have been proposed, researched, developed, and/or commercialized for detection of faults in commercial HVAC equipment and systems. The common thread in all of these systems is monitoring of equipment to determine whether it is operating properly or need service (Westphalen 2003).

The focus of these existing systems is to reduce equipment downtime and save energy by reducing inefficient HVAC system operation. Both manual and automated diagnostic systems are currently under development by the government and private sector (Friedman and Piete 2001). None of the automated diagnostic systems under development are currently aimed at providing either real-time boundary condition data to CBR modeling and simulation tools or to provide assistance with initial or nearly continual commissioning of installed CBR protective systems.

Continuous Commissioning<sup>SM</sup> procedures are currently under development by Texas A&M and others, but these procedures generally rely on manual data analysis of HVAC system performance after automated data collection (Energy Systems Laboratory)

The literature does not show any research specifically aimed at automated CBR protective system diagnostics at this time.

## Summary

Methods of determining and quantifying overall building leakage using fan pressurization and tracer gas techniques for the purpose of studying and assessing impacts on energy usage, indoor air quality, and related issues are well developed. When comparing the generated results from these two techniques, the fan pressurization tests provide direct relationship of airflow to pressure differential, which is suitable for providing boundary conditions for CFD modeling. The tracer gas dilution procedure does not inherently provide such a leakage function.

There are also fan pressurization test methods for measuring air leakage of internal zones and partition walls as well as individual components. These include small-scale laboratory tests and field tests. Based on a review of the literature, however, there is no established protocol for determining the leakage parameters for characterizing a building in its entirety, which is necessary for providing the boundary conditions for CBR contaminant transport modeling. Nor does a process exist for assessing these parameters during a building's service life; a requirement for ensuring that any enacted building response is based on an accurate model.

Criteria for conducting air leakage tests and understanding of the accuracy and uncertainties of the measurements for energy, air quality, and related purposes have been studied to some degree. The ability of the fan pressurization techniques to provide the required level of characterization, accuracy and repeatability needed for studying CBR contaminant transport in buildings is unknown. Past studies concerning IAQ and energy usage have not provided the impetus for investigating such topics.

While limited automated HVAC diagnostic systems exist, no automated diagnostic system for assessing the performance of an installed CBR protective system over a facility's life is known to exist.

## 6 Text References

The bibliographic citations listed in this chapter expand the in-text citations in the preceding chapters of this report.

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## 7 Select Annotated Bibliography

This literature search produced a long list of potentially useful documents. Reviewed publications found to be particularly relevant to this research are abstracted below. Abstracts drawn verbatim from the cited document are marked with [†].

Abstracts copied verbatim from Jennifer McWilliams' summary report, *Energy Performance of Buildings Group*, LBNL-49747 (Environmental Energy Technologies Divisions, Lawrence Berkeley National Laboratory, Berkeley, CA, 01 December 2001) are marked with [††].

A number of additional publications may contain useful information to force protection researchers. Appendix A contains a general (unannotated) bibliography of these publications.

### General Force Protection

Davis, Lynn E., Tom LaTourrette, David E. Mosher, Lois M. Davis, and David R. Howell, *Individual Preparedness and Response to Chemical, Radiological, Nuclear, and Biological Terrorist Attacks* (RAND Public Safety and Justice, Santa Monica, CA, 2003).

This publication identifies strategies that individuals can follow to prepare for and respond to potential chemical, radiological, nuclear, and biological attacks from terrorists. While its focus is on individual response to various terrorist attack scenarios, the publication's response strategies and recommended/not recommended actions are of relevance to developers of facility level force protection and building control strategies. Of particular interest are the six types of catastrophic terrorism scenarios described in Appendix A. Each scenario includes an overview, event history that describes the details and consequences of an attack, a timescale that delineates the different periods of the attack, and an examination of the effect of the attack on services, infrastructure, and other aspects.

Deputy Secretary of Defense Memorandum, Subject: Preparedness of U.S. Military Installations and Facilities Worldwide Against Chemical, Biological, Radiological, Nuclear and High-Yield Explosive (CBRNE) Attack (5 September 2002).

A memorandum from the Deputy Secretary of Defense stating that it is the policy of the Department of Defense to protect personnel on military installations and DOD-owned or leased facilities from CBRNE attacks, to respond to these attacks

with trained and equipped emergency responders, and to ensure installations are able to continue critical operations during an attack and to resume essential operations after an attack. The Department must develop DOD-wide concepts of operations for the preparedness of military installations and DOD-owned or leased facilities against CBRNE attacks. The concepts of operations must address how to deter CBRNE attacks, and if deterrence is not successful, to detect the CBRNE incident, warn and protect personnel from such attacks, avoid any contamination, and respond appropriately to mitigate the impact of the attack. These concepts of operations should preserve critical military capabilities and eventually lead to the restoration of operations at the installation.

Federal Emergency Management Agency (FEMA), *Reference Manual To Mitigate Potential Terrorist Attacks Against Buildings*, FEMA 426 (FEMA, December 2003).

This manual provides guidance to the building science community of architects and engineers, to reduce physical damage to buildings, related infrastructure, and people caused by terrorist assaults. The manual presents incremental approaches that can be implemented over time to decrease the vulnerability of buildings to terrorist threats. Many of the recommendations can be implemented quickly and cost-effectively. FEMA 426 contains many how-to aspects based upon current information contained in FEMA, Department of Commerce, Department of Defense, Department of Justice, General Services Administration, Department of Veterans Affairs, Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health, and other publications. The manual describes a threat assessment methodology and presents a Building Vulnerability Assessment Checklist to support the assessment process. It also discusses architectural and engineering design considerations, standoff distances, explosive blast, and chemical, biological, and radiological (CBR) information. The appendices in this manual include a glossary of CBR definitions as well as general definitions of key terminologies used in the building science security area. The appendices also describe design considerations for electronic security systems and provide a listing of associations and organizations currently working in the building science security area.

FEMA, *Primer for Design of Commercial Buildings To Mitigate Terrorist Attacks*, FEMA 427 (FEMA December 2003).

This publication provides guidance to building designers, owners and state and local governments to mitigate the effects of hazards resulting from terrorist attacks on new buildings. While the guidance provided focuses principally on explosive attacks and design strategies to mitigate the effects of explosions, the document also addresses design strategies to mitigate the effects of chemical, biological and radiological attacks. In addition to applicability to the design of new commercial office, retail, multi-family residential, and light-industrial buildings, many of the concepts presented are also applicable to other building types and/or existing buildings.

Kowalski, W.J., and W.P. Bahnfleth, "Immune-Building Technology and Bioterrorism Defense," *HPAC Engineering* (January 2003).

This article describes primary immune building technologies for controlling airborne pathogens that may be used in bioterrorism. It reviews the effectiveness of

dilution ventilation, filtration, and ultraviolet germicidal irradiation (UVGI) in mitigating the threat to occupants posed by the release of five representative biological weapon (BW) agents in a model multistory building's outside-air intakes, and evaluate the limits of protection provided by these technologies.

Headquarters, U.S. Army Corps of Engineers (HQUSACE), *Design of Collective Protection Shelters To Resist Chemical, Biological, and Radiological (CBR) Agents*, Engineer Technical Letter (ETL) 1110-3-498 (HQUSACE 24 February 1999).

Chemical, biological, or radiological agent threats can come from a wartime attack, a terrorist attack, or from an industrial accident. Protection can be achieved by evacuating the affected area or by using shelters or individual protective equipment (IPE). When evacuation is logistically impossible, passive shelters that use only sealing measures provide limited protection for a short period. For increased protection and longer durations, a preplaced collective protection ventilation system is required. Collective protection provides a toxic-free area (TFA) where personnel can function without individual protective equipment such as a mask and protective garments. This letter provides information and guidance for the design of collective protection (CP) systems, and applies to all HQUSACE elements and USACE commands having military construction and design responsibility.

U.S. Army Edgewood Chemical Biological Center (ECBC) and the U.S. Army Corps of Engineers Protective Design Center (PDC), *Protecting Buildings and Their Occupants from Airborne Hazards*, Technical Instructions (TI) 853-01 (HQUSACE, October 2001).

This document presents a variety of ways to protect building occupants from airborne hazards—to prevent, protect against, and reduce the effects of outdoor and indoor releases of hazardous materials. It contains guidance for building managers, designers, and security planners on how to minimize the potential effects of hazardous materials released in accidents, malicious acts, or natural phenomena. These protective measures can be as simple as defining and implementing a protective action plan. Some are design measures for new construction or retrofit that can reduce the likelihood that releases will affect building occupants. Others are security measures intended to prevent an internal release or an external release close to the building.

U.S. Department of Defense (DOD) *DOD Minimum Antiterrorism Standards for Buildings*, Unified Facilities Criteria (UFC) 4-010-01 (DOD, 8 October 2003).

This document represents a significant commitment by DOD to seek effective ways to minimize the likelihood of mass casualties from terrorist attacks against DOD personnel in the buildings in which they work and live. This specific document is also issued under the authority of DOD Instruction Number 2000.16, *DOD Antiterrorism Standards* which requires DOD Components to adopt and adhere to common criteria and minimum construction standards to mitigate antiterrorism vulnerabilities and terrorist threats. The standards established by this document are minimums set for DOD. Each DOD Component may set more stringent antiterrorism building standards to meet the specific threats in its area of responsibility.

## Modeling and Simulation of Dispersion of Chemical/Biological Contaminants

Cybyk, B.Z., J.P. Boris, and T.R. Young, "A Complex-Geometry CFD Model for Chemical/Biological Contaminant Transport Problems," *1999 DOD HPC User Group Conference, Monterey, CA, June 7-10, 1999*. ‡

Capability of a numerical code, FSAT3d-CT, has been discussed with numerical simulation of external release scenarios about Washington's Pentagon and DC Mall areas. The code was also used for internal release scenarios within the German Village apartment complex, Dugway Proving Ground, UT. The code is based on CFD calculation of the Euler Equation (instead of the Navier-Stokes equation). The external release model has been simulated on an Intel iPSC/860 using about 1.2 million grid points for 6 meter resolution on a super computer. Continuing calibration and expansion into the Navier Stokes equation is required for application towards simulation of internal release models.

Federspiel, C. C., H. Li, D.M. Auslander, D. Lorenzetti, and A.J. Gadgil, "Modeling Transient Contaminant Transport in HVAC Systems and Buildings," *Proceedings of Indoor Air 2002, Monterey, CA*, vol 4, pp 217-222,

and

Sippola, Mark R. and William W. Nazaroff "Modeling Particle Loss in Ventilation Ducts," *Atmospheric Environment* (submitted for publication in 2004). ‡

A mathematical model of the contaminant transport in HVAC systems and buildings is described. The model accounts for transients introduced by control elements such as fans and control dampers. The contaminant transport equations are coupled to momentum equations and mass continuity equations of the air. To avoid modeling variable transport delays directly, ducts are divided into a large number of small sections. Perfect mixing is assumed in each section. Contaminant transport equations are integrated with momentum equations in a way that guarantees mass continuity by using two non-negative velocities for computing the mass transport between elements. Computer simulations illustrate how the model may be used to analyze and design control systems that respond to a sudden release of a toxic contaminant near a building. By coupling transient flow prediction with transient contaminant prediction, the model overcomes a number of problems with existing contaminant transport codes.

Kelly J. Knight, et al., "Physical and Computational Modeling for Chemical and Biological Weapons Airflow Applications," *2002 ASME International Mechanical Engineering Congress and Exposition, New Orleans, Louisiana, November 17-22, 2002*. ‡

A CFD modeling of flow distribution around a test model building has been presented in the paper. The CFD modeling used a commercial numerical package (FLUENT) to calculate the velocity profiles and pressure contours around the building external envelope. The calculation was compared to the experimental results from the test model. The experiments used the INEEL's unique large Matched-Index-of-Refractive flow system (INEEL – Idaho National Engineering and Environmental Laboratory.) The predicted velocity profiles from above the

building and in front of the building were in good agreement with the measurements. It should be noted that the accurate determination of the pressure distribution over the building external envelope is the critical boundary condition for CFD calculation of flow field inside the building.

Liu, D.L. and W.W. Nazaroff, "Modeling Pollutant Penetration Across Building Envelopes," *Atmospheric Environment* (2001), vol 35, pp 4451-4462. ‡

As air infiltrates through unintentional openings in building envelopes, pollutants may interact with adjacent surfaces. Such interactions can alter human exposure to air pollutants of outdoor origin. [The authors] present modeling explorations of the proportion of particles and reactive gases (e.g., ozone) that penetrate building envelopes as air enters through cracks and wall cavities. Calculations were performed for idealized rectangular cracks, assuming regular geometry, smooth inner crack surface and steady airflow. ... For wall cavities, fiberglass insulation is an efficient particle filter, but particles would penetrate efficiently through uninsulated wall cavities or through insulated cavities with significant airflow bypass. ... Not enough is yet known about the detailed nature of pollutant penetration leakage paths to reliably predict infiltration into real buildings.

Mora, L., A.J. Gadgil, and E. Wurtz, "Comparing Zonal and CFD Model Predictions of Isothermal Airflows to Experimental Data," *Indoor Air 2003*, vol 13, pp 77-85. ‡

It is inappropriate to use the assumption of instantaneously well-mixed zones to model airflows and pollutant transport in large indoor spaces. We investigate two approaches for describing the details of airflows in large indoor spaces, for accuracy and suitability for integration with multi-zone infiltration models. One approach, called the zonal method, was developed over the last 15 years to provide an improvement over the well-mixed assumption. The second approach is the use of a computational fluid dynamics simulation using a coarse grid model of the large indoor space. [The authors] compare velocity predictions from different formulations of zonal methods and coarse-grid *k-e* computational fluid dynamics (CFD) models, to measurements, in a 2D mechanically ventilated isothermal room. [Their] results suggest that, when airflow details are required, coarse-grid CFD is a better-suited method to predict airflows in large indoor spaces coupled with complex multi-zone buildings, than are the zonal methods. Based on the comparison of pressure predictions from different models, [they] offer guidance regarding the coupling of a model of detailed airflow in large spaces to algebraic multi-zone infiltration models.

Persily, A.K., "Myths About Building Envelopes," *ASHRAE Journal* (March 1999), pp 39-45.

It is often assumed that commercial and institutional buildings are fairly airtight and that envelope air leakage does not have a significant impact on energy consumption and indoor air quality in these buildings. Furthermore, it is assumed that more recently constructed buildings are tighter than older buildings. However, very little data is available on the airtightness of building envelopes in commercial and institutional buildings. The data that exist show significant levels of air leakage in these buildings and do not support correlations of airtightness with building age, size or construction. This article presents the available airtightness data and the limited conclusions that can be drawn from these data.

Price, P.N., M.D. Sohn, A.J. Gadgil, W.W. Delp, D.M. Lorenzetti, E.U. Finlayson, T.L. Thatcher, R.G. Sextro, E.A. Derby, S.A. Jarvis, *Protecting Buildings From a Biological or Chemical Attack: Actions To Take Before or During a Release*, LBNL-51959 (Lawrence Berkeley National Laboratory, 11 February 2003).

This report presents advice on how to operate a building to reduce casualties from a biological or chemical attack, as well as potential changes to the building (e.g., the design of the ventilation system) that could make it more secure. It also documents the assumptions and reasoning behind the advice. The particular circumstances of any attack, such as the ventilation system design, building occupancy, agent type, source strength and location, and so on, may differ from the assumptions made here, in which case actions other than our recommendations may be required; we hope that by understanding the rationale behind the advice, building operators can modify it as required for their circumstances.

U.S. Army Edgewood Chemical Biological Center (ECBC) and the U.S. Army Corps of Engineers Protective Design Center (PDC), *Protecting Building and Their Occupants from Airborne Hazards*, Technical Instruction 853-01 (October 2001).

See Force Protection above.

U.S. Defense Threat Reduction Agency, *Hazard Prediction and Assessment Capability (HPAC)*, *User Guide Version 4.0.1*, HPAC-UG-01-U-R0C0 (April 19, 2002).

The HPAC software predicts the effects of hazardous nuclear, biological, and chemical (NBC) material releases into the atmosphere and its collateral effects on civilian and military populations. This counterproliferation and counterforce tool assists war fighters in weaponizing targets containing weapons of mass destruction (WMD) and in emergency response to hazardous material releases. HPAC employs integrated source term models, high-resolution weather data, and particulate transport algorithms to model hazard areas and human collateral effects in minutes. HPAC estimates the NBC hazards associated with releases from either facilities or weapons. HPAC predicts NBC hazards from incidents such as the following:

- Nuclear Facility Accidents (Chernobyl, Ukraine)
- Nuclear Weapon Explosions (Hiroshima, Japan)
- Nuclear Weapon Incident/Accident, “Broken Arrow” (Palomares, Spain)
- Radiological Weapon Incident
- Chemical Facility Damage (Bhopal, India)
- Biological Facility Damage (Sverdlovsk, Russia)
- Chemical Weapons (Kamasiyha, Iraq)
- Biological Weapons (Yokosuka, Japan [alleged use by Aum Shin Rikyo])

HPAC was designed to be used by two types of users, operational and analytical. Operational users include pilots, soldiers, and commanders—in other words, field users responding to actual or expected events. Analytical users (analysts) generally are involved in research and development. HPAC generally includes default values for user inputs in order to simplify complex input for operational users. Analytical users may change these default inputs based on their subject matter expertise.

U.S. Environmental Protection Agency (USEPA), *AERMOD: Latest Features and Evaluation Results*, EPA-454/R-03-003 (USEPA, June 2003). ‡

AERMOD is an advanced plume model that incorporates updated treatments of the boundary layer theory, understanding of turbulence and dispersion, and includes handling of terrain interactions. The model was formally proposed by EPA in April 2000 as a replacement for the ISCST3 model. Several model enhancements were made as a result of public comment, including the installation of the PRIME downwash algorithm. The latest version of the model, version 02222, has been placed on EPA's web site for beta test purposes. This paper reviews the latest features and updated evaluation results for AERMOD version 02222.

## Intelligent Building Control

ASHRAE Presidential Ad Hoc Committee for Building Health and Safety Under Extraordinary Incidents, *Risk Management Guidance for Health, Safety, and Environmental Security under Extraordinary Incidents* (ASHRAE, Atlanta, GA, 26 January 2003).

Extraordinary incidents, whether caused by war, terrorism, accident or natural disaster, can impact immediate human needs including survival and safety, and also such longer-term needs as air, water, food, and shelter. ASHRAE's expertise in heating, ventilation, air-conditioning, and refrigeration (HVAC&R), and its knowledge of building envelope performance, intake and exhaust air control, air and water treatment, and food preservation is critical in addressing life-safety, and environmental security. ... The *objective* of this report is to provide guidance for new and existing buildings regarding protection of air, water, and food systems within buildings. The *scope* of this report pertains to public use and assembly buildings; commercial, institutional, and educational facilities; and other areas of public assembly such as stadiums, coliseums, and vehicle tunnels and subways. This scope also pertains to those areas of industrial and manufacturing facilities that affect occupancy.

Bushby, Steven T., "Integrating Fire Alarm Systems with Building Automation Control Systems," *Fire Protection Engineering* (Society of Fire Protection Engineers, Bethesda, MD, Summer 2001), pp 5-11.

Integrating fire alarm systems with building automation systems can result in many economic and operational benefits. Such integration requires communication standards and careful design practices. ... Maintaining the integrity of fire alarm systems when they are integrated with other building systems requires more than just communication standards. Best design practices, appropriate testing procedures, and modernized building are also needed.

Chang, Seongju, *A Hybrid Computational Model for Building Systems Control*, Thesis (School of Architecture, Carnegie Mellon University, 1999). ‡

The increased complexity in building systems integration provides a new challenge for building operation process. A wide distribution of the direct digital control approach has inspired researchers and engineers to pay more attention to

the computational solutions in building control. The enhanced knowledge about building systems behaviors as well as the increased computing power make attractive the potential use of a computational building model as the agent to carry on building control task. On the other hand, some simulation programs are computationally too intensive to be effective for real-time control purpose. A machine learner can address this problem. However, it often requires large amount of data for training or retraining, which makes the technique inevitably sensor-dependent. This thesis intends to demonstrate that analytical approaches (i.e., simulation) and inductive learning methods (i.e., neural networks) can cooperate to facilitate building systems control. In this process, the role of a simulator is augmented as the source of the system knowledge by which a supervised learner, implemented in neural networks, is trained for faster predictions. A machine learner, trained either to replace a simulator or to predict the simulation error, serves as the pivotal component for a better predictor through a hybridization process.

Continental Automated Buildings Association, *Technology Roadmap for Intelligent Buildings* (Ottawa, Ontario, Canada, 2002).

This Technology Roadmap explores and explains the current status and imminent opportunities offered by the accelerating evolution and use of intelligent building technologies. The focus is on commercial, institutional and high-rise residential buildings, both new projects and retrofits, in a five-year time horizon. ... Intelligent buildings apply technologies to improve the building environment and functionality for occupants/tenants while controlling costs. ... An efficient integrated system enables a modern, comprehensive access and security system to operate effectively and exchange information with other building systems. ... To integrate these systems and exchange information effectively, a ubiquitous and reliable communications infrastructure is needed. ... The future will require full interoperability, with information exchanged among all systems. There is an opportunity for technologies that translate protocols and conventions so that systems are fully interoperable.

Department of Health and Human Services, Centers for Disease Control and Prevention, *Guidance for Filtration and Air-Cleaning Systems To Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks*, DHHS (NIOSH) Pub. No. 2003-136 (National Institute for Occupational Safety and Health, Cincinnati, OH, April 2003).

This document discusses air filtration and air-cleaning issues associated with protecting building environments from an airborne chemical, biological, or radiological (CBR) attack. It provides information about issues that should be considered when assessing, installing, and upgrading filtration systems—along with the types of threats that can be addressed by air-filtration and air-cleaning systems. It is intended to provide guidance regarding measures that may be taken to prepare for a potential CBR attack, rather than in response to an actual CBR event. The complex issues regarding response and cleanup in the aftermath of an actual CBR event are situation dependent and are beyond the scope of this guidance document.

Department of Health and Human Services, Centers for Disease Control and Prevention, *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks*, DHHS (NIOSH) Pub. No. 2002-139 (National Institute for Occupational Safety and Health, Cincinnati, OH, May 2002).

This guide focuses on deterrence through “hardening” strategies designed to transform buildings into less attractive targets. The guide identifies three categories of these deterrents: (1) Those that increase the difficulty of introducing a CBR agent into a building’s environment; (2) Those that increase the opportunity to detect terrorists before they carry out the release of a CBR agent; (3) Those that enhance the opportunity or ability, through mechanical or procedural measures, to mitigate the effect of a CBR release. The crucial first stage for achieving these deterrents before any remedial measures are taken is to “know your building.” Depending on the actual nature, age, operational requirements, and condition of a particular system, what seems an “obvious” solution may have disastrous results. Therefore, the guide advises building managers to conduct a thorough review of building system design and operations to establish a baseline understanding of the actual condition and function of the equipment, as opposed to relying on schematics and other records that may be out-of-date or simply inaccurate. The guide includes a list of considerations as examples of the nature of information that should be gathered.

Federspiel, C.C., H. Li, D.M. Auslander, D. Lorenzetti, and A.J. Gadgil, “Modeling Transient Contaminant Transport in HVAC Systems and Buildings,” *Indoor Air 2002 Conference, Monterey, CA, June 2002*. ‡

A mathematical model of the contaminant transport in HVAC systems and buildings is described. The model accounts for transients introduced by control elements such as fans and control dampers. The contaminant transport equations are coupled to momentum equations and mass continuity equations of the air. To avoid modeling variable transport delays directly, ducts are divided into a large number of small sections. Perfect mixing is assumed in each section. Contaminant transport equations are integrated with momentum equations in a way that guarantees mass continuity by using two non-negative velocities for computing the mass transport between elements. Computer simulations illustrate how the model may be used to analyze and design control systems that respond to a sudden release of a toxic contaminant near a building. By coupling transient flow prediction with transient contaminant prediction, the model overcomes a number of problems with existing contaminant transport codes.

Felker, Larry, “Use Of Isolation, Economizer & Smoke Control Dampers for Commercial Building Space Isolation From Chemical, Biological, and Radiation Attack,” *HPAC Engineering* (2004, publication pending).

There are many tactics that could assist in protecting building occupants that need to be considered when analyzing security procedures in the case of airborne CBR attack. ... There are no published standards as of this writing, but ASHRAE and NIOSH have made guidelines available. ... The simpler a system, the better it can be understood, maintained, tested, and used to the best of its abilities by an operator who is not expert at the system. Commissioning, documentation, maintenance manuals, instructions, and training are critical. There are thousands of possible combinations of air handling and floor layout plans that can exist; almost every building’s duct and damper arrangements are

unique. In all cases there are principles taken from fire and smoke control that guide any design approach regardless of the type of system. ... The engineering designer must consider all these factors in order to facilitate the system's use by staff, fire fighters, or police.

Finkelstein, Hal, *HVAC Systems for Bioterrorism Protection—A Guide to Engineering, Design and Operations* (The National Resources Center, Inc., Coral Springs, FL, 2001).

This publication presents concepts that must be considered in the design, installation, and operation of facilities to protect building occupants from potential bioterrorism attacks, including anthrax, smallpox, nerve gas, sarin gas and all other major Bio and Chemical warfare agents. Basic methods of movement and spread of these agents within buildings and their HVAC systems are covered as well as how contamination may be controlled through ventilation, filtration, and adsorption.

Herron, Dale L., William J. Croisant, Justin B. Berman, Michael K. McInerney, Paul H. Nielsen, David M. Bailey, Aaron J. Averbuch, Annette L. Stumpf, Beth A. Brucker, Robert F. Quattrone, and Gordon L. Cohen, *Integrated Smart Building Conceptual Design for Rodman Materials Research Laboratory*, ERDC/CERL TR-00-32 (U.S. Army Corps of Engineers Engineer Research and Development Center, Construction Engineering Research Laboratory [ERDC-CERL], Champaign, IL, December 2000).

This report describes a *Smart Building Demonstration Initiative* at Aberdeen Proving Ground. The purpose of the initiative was to demonstrate the benefits of using *smart building technologies* in Army facilities by retrofitting an existing facility followed by later construction of a new facility with smart systems integrated at the earliest stages of design. A *smart building* would integrate “new technologies from such areas as computer automation, space-age materials, diagnostic sensors, and energy management to automate, measure, and control many different conditions.” Such a building would enable facility personnel to make “more meaningful decisions regarding facility conditions, environmental quality, personnel comfort, physical security, fire prevention and/or detection, electric and mechanical fault detection, moisture penetration, and communications.” Tasks completed under the initiative included conducting assessments of existing facility systems and user needs, identifying applicable smart building technologies, developing a conceptual design for smart technology retrofits, and developing an implementation plan.

Jaeger, Thomas W., “Smoke & Fire Control: Safe & Sound Thinking,” *Engineered Systems* (November 2002). ‡

The emergence of performance-based fire safety design has finally made fire safety a partner with the traditionally performance-based disciplines of building security design and chemical/biological/radiological (CBR) building protection. Fire safety and security (with or without CBR building protection) are often a significant part of any major construction effort. However, a disconnect often exists between life safety requirements (get every occupant out of the building safely) and security (prevent unauthorized access). While there are prescriptive code requirements that generally address these situations, there is little consid-

eration for new technologies that have yet to be written into the code, but that may provide a superior solution.

Klote, John H., and James A. Milke, *Principles of Smoke Management* (ASHRAE Publications, Atlanta, GA, 2002).

From zoned smoke control to pressurized stairwells, [this book] is an exhaustive treatment of smoke management. Recent advancements discussed in the book include heat release rate, toxicity of smoke, natural atrium venting, plugholing, smoke stratification, smoke detection and tenability systems. Methods of analysis include equations, network flow models, zone fire models, scale modeling and hazard analysis. Computational fluid dynamics (CFD) is also addressed. The book includes a CD containing five different computer programs, and provides discussion of the CD and several sample calculations. The CD can be used for smoke management design and analysis.

Lorenzetti, David, "Predicting Indoor Pollutant Concentrations, and Applications to Air Quality Management," *Joint WHO-JRC-ECA Workshop* (Lawrence Berkeley National Laboratory, October 2002).

Because most people spend more than 90 percent of their time indoors, predicting exposure to airborne pollutants requires models that incorporate the effect of buildings. Buildings affect the exposure of their occupants in a number of ways, both by design (for example, filters in ventilation systems remove particles) and incidentally (for example, sorption on walls can reduce peak concentrations, but prolong exposure to semivolatile organic compounds). Furthermore, building materials and occupant activities can generate pollutants. Indoor air quality depends not only on outdoor air quality, but also on the design, maintenance, and use of the building. ... Indoor air quality models simulate the processes, such as ventilation and filtration, that control pollutant concentrations in a building.

Sohn, Michael D., Pamela Reynolds, Navtej Singh, and Ashok J. Gadgil, "Rapidly Locating and Characterizing Pollutant Releases in Buildings," *Journal of the Air and Waste Management Association* (Pittsburgh, PA, December 2002), vol 52, pp 1422-1432. ‡

Releases of airborne contaminants in or near a building can lead to significant human exposures unless prompt response measures are taken. However, possible responses can include conflicting strategies, such as shutting the ventilation system off versus running it in a purge mode or having occupants evacuate versus sheltering in place. The proper choice depends in part on knowing the source locations, the amounts released, and the likely future dispersion routes of the pollutants. We present an approach that estimates this information in real time. It applies Bayesian statistics to interpret measurements of airborne pollutant concentrations from multiple sensors placed in the building and computes best estimates and uncertainties of the release conditions. The algorithm is fast, capable of continuously updating the estimates as measurements stream in from sensors.

Sohn, M.D., R.G. Sextro, A.J. Gadgil, and J.M. Daisey, "Responding to Sudden Pollutant Releases in Office Buildings: 1. Framework and Analysis Tools," *Indoor Air Journal* (Blackwell Publishing, Munksgaard, Copenhagen, Denmark, September 2003), vol 13, No. 3, pp 267-276. ‡

We describe a framework for developing response recommendations to unexpected toxic pollutant releases in commercial buildings. It may be applied in conditions where limited building—and event-specific information is available. The framework is based on a screening-level methodology to develop insights, or rules-of-thumb, into the behavior of airflow and pollutant transport. A three-stage framework is presented: (1) develop a building taxonomy to identify generic, or prototypical, building configurations; (2) characterize uncertainty and conduct simulation modeling to predict typical airflow and pollutant transport behavior; and (3) rank uncertainty contributions to determine how information obtained at a site might reduce uncertainties in the model predictions. The approach is applied to study a hypothetical pollutant release on the first floor of a five-story office building. Key features that affect pollutant transport are identified and described by value ranges in the building stock. Simulation modeling provides predictions and uncertainty estimates of time-dependent pollutant concentrations, following a release, for a range of indoor and outdoor conditions. In this exercise, we predict concentrations on the fifth floor to be an order of magnitude less than on the first, coefficients of variation greater than 2, and information about the HVAC operation and window position most reducing uncertainty in predicted peak concentrations.

## Building Envelope Performance /Air Leakage

Bahnfleth, William P., K. Grenville, and Brian W. Lee, "Protocol for Field Testing of Tall Buildings To Determine Envelope Air Leakage Rate," *ASHRAE Transactions* (1999), vol 105, p 27-37.

The objective of the project was to develop a relatively simple, accurate method for testing the overall envelope leakage rate of tall buildings. Two fan pressurization test techniques were developed and tested on two buildings. One employed a floor-by-floor blower door method and the other used the building's HVAC air-handling unit.

In the floor-by-floor blower door test, the envelope leakage of each floor is determined independently. Sealing air paths and achieving zero pressure differentials through the use of blower doors fans prevent the internal leakage between the test floor and adjacent floors. The fans can be placed in doorways to stairwell shafts or building openings such as an operable window. This method offers the capability of determining envelope leakage for each individual floor rather than for the entire building as a whole.

In the air handler method, the building supply fans, located in the mechanical rooms, provide the necessary controlled pressurization. The envelope leakage through each air-handler zone can be measured. The building portion tested using this method can vary in size from the area served by one supply fan to the entire building. The rapidity of installation of the flow measurement devices and the use of in-place fans for air supply are significant advantages to using this

method. The outdoor airflow rate can be determined by tracer gas dilution, orifice plate or pitot traverse.

Both procedures were tested on two separate different buildings and evaluated based on the criteria developed for each test, value of information acquired, ease of use and degree of building operation disruption. The researchers surmised that the best method to be used for a particular building depended on certain characteristics of that building. The use of the floor-by-floor method may not be practical for buildings that have numerous interfloor leakage paths resulting from supply and return shaft penetrations.

Guidelines were proposed for conducting accurate air leakage tests on tall buildings using the two methods with recommendations from existing standards and the experiences derived from this study.

Depani, Sebastiano, and Paul Fazio, "Airtightness Testing and Air Flow Modelling of a Three-Unit Multifamily Building," *Canadian Conference on Building Energy Simulation June 2001 Ottawa Canada*.

This paper presents a ventilation case study for a 3-unit multifamily building typical of those found in Montreal. The external envelope leakage and internal leakages between the units were determined using the single fan blower door method. This method produces more valuable data than can be obtained by performing a single whole building pressurization test. A testing protocol of running single fan blower door tests on all three units at a pressure differential of 50 Pa with the outside environment was employed. The flow exponent ( $n$ ) was assumed to be equal to 0.65. The flow coefficients for all exterior flow paths and the two interior flow paths (between units 1 and 2, and units 1 and 3) are determined by balancing the flows.

A multizonal airflow computer model was used in conjunction with the fan-pressurization data to demonstrate natural ventilation trends on a unit-per-unit basis for the building. Some rough assumptions were made concerning the distribution of the leakage within the units. Two additional sets of simulations were performed to demonstrate the impact on building ventilation resulting from sealing the attic spaces and retrofitting with exhaust fans on building ventilation.

The paper demonstrates how blower door test results can be used with a simple multizone modeling tool to investigate ventilation as a function of outdoor temperature and wind speed. The author lists several studies that have focused on the measurement of interzonal and envelope leakage in multiunit buildings.

Colliver, D.G., W.E. Murphy, and W. Sun, "Development of a Building Component Air Leakage Data Base," *ASHRAE Transactions* (1994), vol 100, No. 1, pp 292-305.

A component air leakage table that is included in the 1989 ASHRAE *Handbook of Fundamentals* provides valuable information to designers, builders and practitioners. Considerable research and data have become available since the table was developed. This paper documents the extensive effort to compile, catalog into a database, and analyze the available building component air leakage data for the purpose of developing an updated revision to the table to be included in the forthcoming editions of the ASHRAE handbook.

Within the paper, the authors also discuss the different techniques for measuring building component air leakage, which include: (1) sealing the component with a chamber, (2) balanced fan pressurization, (3) selective progressive sealing and (4) controlled laboratory conditions. Several methods for reporting test results using these techniques are also presented.

Feldman, D, T. Stathopoulos, C. Cosmulescu, and H. Wu, "A Simple Apparatus for the Evaluation of Air Infiltration Through Building Envelope Components," *Journal of Wind Engineering and Industrial Aerodynamics* (1998), vol 77.

The paper discusses the development of a small simple apparatus designed, built and calibrated; and then tested for the determination of air leakage through building envelope components such as simple and composite walls. The ASTM Standard E 283-91 was followed when developing the apparatus. Its basic configuration is two chambers—each 1 m by 1 m by 0.5 m long having a wooden frame for the installation and sealing of the test specimen between the two chambers. Closed cell foam gaskets are used to seal between the frame holding the specimen and the two chambers. Pressure differences are applied between the chambers, and the flow of air through the specimen is then measured. The results of test experiments conducted on samples of gypsum board and of plywood sheathings resulted in air leakage measurements that are in agreement with the published data.

Furbringer, J-M., and C-A. Roulet, "Study of the Errors Occurring in Measurement of Leakage Distribution in Buildings by Multifan Pressurization," *Building Environment* (1991), vol 26, No. 2.

This paper presents a study of the errors and confidence limits of the results from performing air leakage testing on multizone buildings using two different multifan pressurization methods. The authors' purpose for the study was to show how carefully fan pressurization results should be used in modeling building airflow.

Both methods, deduction and guarding zone, can be used to determine air leakage on external and internal walls. The deduction method consists of varying the pressure in the pressure ring while keeping the pressure in the test room constant. The pressure ring can be described as the rooms that are around the test room that have their pressures controlled and different from the outside pressure. In the guarding zone method, the pressure in the pressure ring is held at the same level as the guarded zone (test room).

The researchers discuss the estimators of errors for each of the methods in detail. Their findings show that error analysis is very important when using multizone pressurization techniques. The primary instrumental source of error in the guarded zone method is the control of the zero pressure difference between the guarding and measured zones. The accuracy of the airflow measurements is the critical source of error in the deduction method. For typical conditions, the guarded zone technique is generally the more accurate of the two. The confidence intervals for either method can be large and may be of the same order of magnitude as the results themselves. This seems to indicate that there is a need for more accurate instruments to be used in these test methods. The authors also pointed out that a good "design of experiment" would include running the

tests at the lowest and highest pressures that are compatible with the instrumentation in order to determine the air leakage characteristics.

Grinzato, E., V. Vavilov, and T. Kauppinen, "Quantitative Infrared Thermography in Buildings," *Energy and Buildings* (December 1998). ‡

A methodology, based on the solution of the inverse heat transfer problem, for the detection and evaluation of flaws in buildings is discussed in this paper. The temperature varying in space and time is recorded by thermographic equipment and each point belonging to the inspected area is analyzed quantitatively. Data are processed to give a map of defects of the wall, based on the most suitable local thermal parameter. The thermal-physical aspects of different defects are studied, along with the description of simplified models to interpret surface temperature data. The building envelope is examined mainly in transient thermal regime. Testing procedures using periodic or pulse heating of the surface are described. The theoretical analysis is used to predict temperature evolution and properly design the test. A detectability comparison among different procedures is performed. Experimental results are reported for insulation deficiencies and thermal bridges evaluation, air leakage detection and moisture content mapping.

Heidt, F.D., and H. Werner, "Microcomputer-aided Measurement of Air Change Rates," *Energy and Buildings* (1986), vol 9, pp 313-320. ‡‡

Air change rates are measured by a non-dispersive one-beam IR gas analyzer using the decay and constant-emission methods with nitrous oxide as tracer gas. Disturbing influences due to H<sub>2</sub>O and CO<sub>2</sub> are low. The analyzer is coupled via a RS-232-C interface to a microcomputer, which is programmed to service the following functions: (1) calibration, (2) preparation and control of measurements, (3) recording, displaying and storing of data, (4) evaluation of results, and (5) error analysis. The implemented programs provide an instant access to results. The whole equipment is installed in compact form on a mobile rack. Measurements have been taken in a university laboratory to examine air change rates with (1) closed door and window, (2) open door only, and (3) tilted window only. Typical results are given and show where the decay method or the constant emission method is more appropriate.

Kvisgaard, B., and P.F. Collet, "Accuracy and Development of Tracer-Gas Measurement Equipment," *10<sup>th</sup> AIVC Conference, Espoo, Finland, 25-28 September, 1989* (February 1990), vol 2, pp 1-16. ‡‡

In 1979 a project was launched at the Technological Institute, Copenhagen with the purpose of developing a method for continuous measurement of air change rates in occupied dwellings. Today—10 years later—we can introduce the first generation of mass-produced measuring equipment performing measurements of air change rates employing the method of constant concentration of tracer gas.

The principles used in the first model, which was introduced 1981, are largely identical to those used in the latest model. However, components and programs have been changed several times. Furthermore, through the years new programs that expand the capability of the measuring equipment have been developed. The paper will discuss the development that has taken place over the 10 years, which problems have caused the biggest trouble and how they were solved. Also, the types of measurement performed with the equipment will be touched upon,

and we shall take a closer look at a couple of special measurements. Finally, the accuracy of the equipment as well as the cost of reaching today's level of development will be discussed.

McWilliams, Jennifer, *Review of Airflow Measurements*, LBNL-49747 (Energy Performance of Buildings Group—Environmental Energy Technologies Division, Lawrence Berkeley National Laboratories, Berkeley CA, 1 December 2002).

Lawrence Berkeley National Laboratories published a literature review of techniques for measuring airflow within buildings. The airflows that are discussed include flow within and between rooms and zones, across the building envelope and through the mechanical air distribution systems. Along with describing techniques for measuring air velocity, the report discusses techniques for measuring air flow across building boundaries due to pressure gradients caused by wind effects, stack effect and HVAC system operation. These techniques include fan pressurization, tracer gas, acoustic methods for leak size determination, the Delta Q test to determine duct leakage flows, and flow hood measurements. Selected papers are annotated, and a bibliography is included for each topic with full abstracts.

Modera, M.P., and M.K. Herrlin, "Investigation of a Fan-Pressurization Technique for Measuring Interzonal Air Leakage," *Air Change Rate and Airtightness in Buildings ASTM 1067*, ASTM 1067 (ASTM Philadelphia 1990).

This paper presents an investigation into the complex problem of predicting airflow in multi-zone buildings. In the introduction, the paper discusses past experiences of using several multizone leakage measurement techniques. These include two that were investigated by the authors. One of these techniques used six blower doors simultaneously to measure the total envelope leakage of a six-unit apartment, coupled with single blower door measurements to measure the leakage area for each apartment. The exterior envelope leakage was then separated from the interior interzonal leakage. The second technique used two blower door tests run simultaneously to measure the leakage for each interzonal flow path. Based on the results of these investigations, it was concluded that the measurements for multizone buildings are more sensitive to wind than measurements of single zone buildings. This may be attributed in part to the fact that multizone buildings are usually taller and therefore exposed to higher wind speeds.

To address the issue, the researchers applied a two-blower door technique for determining air leakage between a primary and secondary zone of a building. One fan is placed between the secondary zone and the primary zone and one is placed between the primary zone and outside. The primary-outdoor pressure differential ( $\Delta P_{po}$ ) is held to a constant (e.g., 50 Pa) and the primary-secondary pressure differential ( $\Delta P_{ps}$ ) is varied. For several increments of  $\Delta P_{ps}$  the two flow rates ( $Q_{pout}$ ,  $Q_{ps}$ ) that are required to maintain the constant  $\Delta P_{po}$  are recorded. Keeping  $\Delta P_{po}$  at a high constant value (50 Pa) reduces the wind effects and allows for better fan controllability.

The effectiveness of this technique was evaluated by conducting simulations using a Multi-zonal Model "MOVECAMP," an infiltration and ventilation simulation program. The uncertainties of measuring leakage due to several factors were characterized. The findings of the simulations indicate that wind plays an

important role in the uncertainties associated with Interzonal leakage measurements. Wind induced uncertainties in the determined leakage parameters derived from the blower door technique do not exceed 10 percent for wind speeds less than 11 MPH. An additional conclusion derived from the study is that the methodology and simulation assumptions that were chosen by the researchers appear to be close to a lower limit on the uncertainties induced by the wind.

Musser, Amy, and Oliver Schwabe, "Validation and Calibration of a Multizone Network Airflow Model with Experimental Data," *Canadian Conference on Building Energy Simulation June 2001* (Ottawa Canada, 2001).

This paper describes the development and refinement of a multizone (MZ) network airflow model to represent a 2-story classroom office building at four different stages. The model is initially developed at the construction stage. Refinement of the building air leakage is then performed based on fan pressurization tests, and further refined based on measuring actual fan flow rates. Brief descriptions of these models are:

Construction Stage Model. A hybrid approach that included a review of architectural plans and published leakage data for the particular exterior wall construction, and doors and windows was used. The researchers assigned a distributed envelope leakage value of  $0.75 \text{ cm}^2/\text{m}^2$  for exterior walls to provide an overall leakage rate of  $1.1 \text{ cm}^2/\text{m}^2$  when combined with doors and windows. Interior partitions, ceilings and floors were modeled with twice the leakage ( $1.5 \text{ cm}^2/\text{m}^2$ ) of exterior walls. The air handling system with diffuser flows were specified based on the mechanical design drawings.

Fan Pressurization Model. Fan pressurization tests were conducted, which indicated that the building envelope leakage was four times higher than the value assigned for the construction model. The overall leakage rate was changed to  $4.3 \text{ cm}^2/\text{m}^2$  and the exterior wall leakage rate and interior wall leakage rate were increased by a factor of four.

Measured Flow Rate Model. A field validation of all the fan driven flow rates for exhaust fans and supply and return ducts were conducted and put into the model to adjust the air handling system parameters.

A fourth model makes use of automated tracer gas decay tests to adjust the flow rates to individual rooms. All four of these MZ model predictions are then compared to additional tracer gas decay tests. The experimental setup is described and an evaluation of the model's ability to simulate the conditions of the test is evaluated for each level of refinement.

The flow rates between zones within the building were predicted and compared for each of the four models by running simulations with the CONTAMW MZ model software. The authors point out the difficulty of determining input boundary parameters, especially those related to envelope leakage. Buildings have many leakage paths and the leakage associated with identical components can vary significantly with the construction used. Fan flows are easier to estimate based on the mechanical system design.

Building leakage characteristics are understood to be important contributors to building airflow. Because the flow in the test building was fan-driven, the predictions using the first two models were not very different from each other. This would not be expected if the model was run in the absence of fan driven flow –

the building leakage would have a much greater impact. Of the experimental techniques used for refinement, the tracer gas decay tests required the most effort. The tracer gas decay tests required long-term installation of tubing, measuring equipment and an automation protocol. The fan pressurization tests were done in a day.

The research found that proper definition of the fan driven flows proved to be the most important experimental measurement contributing to agreement of the model and the experiment. This was a result of the building air exchange rate being driven by fan flow and not building leakage. Had the tests been run with no fan flow, proper definition of the building envelope leakage would have been more critical.

Proskiw, G., and A. Parekh, "A Proposed Test Procedure for Separating Exterior Envelope Air Leakage from Interior Partition Leakage," *Performance of Exterior Envelopes of Whole Buildings, VIII, December 2001 Florida*

This study proposes a new airtightness test procedure for separating exterior envelope air leakage from interior partition leakage when testing a single zone within a multizone building. The technique permits the interior leakage to be measured and then subtracted from the overall leakage of the zone to obtain the exterior leakage. When performing conventional multifan pressurization tests to separate these two leakage components on larger buildings, very large fans may be required to achieve zero-pressure differential with adjacent zones. This proposed procedure attempts to provide a comparatively simpler and less expensive means for separating these leakages by not requiring exact equalization, but only modification of the partition pressure differentials through use of a second fan.

To gain insight into the functionality of the new test procedure under field conditions, a series of trials were carried out on two buildings. The results were mixed but encouraging. To further develop the procedure and better identify its capabilities and limitations, a laboratory facility has been constructed to evaluate the test method. Additional efforts to refine and streamline the analysis procedures are ongoing.

Shaw, C.Y., "Methods for Conducting Small-Scale Pressurization Tests and Air Leakage Data of Multi-Story Apartment Buildings," *ASHRAE Transactions* (1980), vol 86, pt 1, pp 241-250.

This paper describes experiments conducted by the National Research Council of Canada for developing methods for conducting small-scale pressurization tests to determine air leakage characteristics for walls and individual components of wall assemblies such as floor-wall joints, windows and windowsills. The motivation for this research was to be able to quantify overall leakage rates for assessing effects on energy consumption and evaluating conservation measures on buildings where full scale air leakage measurements cannot be performed. These tests required construction of test chambers that are sealed around the perimeter of the test area being measured and the use of portable fans for developing pressure differences in the test chambers. The researchers used additional fans for balancing the pressure in the test chamber with surrounding rooms.

The paper describes and provides diagrams of various experimental setups for measuring air leakage of walls directly. Test chambers made of plywood with polyethylene sheet surfacing were sealed with duct tape to the perimeter sur-

faces of the test wall. Air leakages of individual wall components were measured using two methods – direct and indirect. The direct method was very similar to that used for the walls with modifications required for the pressure balancing and test chamber. The test chamber was constructed to only enclose the portion of the wall containing the component to be tested. The indirect method uses the setup that is employed in the direct method used for walls except that the component being measured is sealed. The difference in leakage before and after masking the component makes up the air leakage flow of the masked component.

Findings showed that when testing windows and determining air leakage, the window and frame-wall joint should be tested as one assembly. For the same window products in different buildings having different construction, and even in the same buildings having the same construction, the assembly when measured with the frame-wall joint gave drastically different air leakage values. This indicates the importance of the frame-wall joint in the overall leakage of the window component. Testing in this manner also reduced the work required in setting up and running the tests.

Running a series of tests validated the requirement for pressure balancing. Some pressurization tests were also performed to investigate the difference in running positive and negative pressures. No appreciable difference was found when testing wall-floor joints and there was at most 12 percent difference found for windows (both higher and lower values were measured).

In comparing the contributions of the various wall assembly components, windows (including frame wall joints) can be the main contributor of air leakage (up to 70 percent of the total leakage). Floor-wall joints and windowsills accounted for up to 50 and 30 percent respectively. Only one building had smooth plastered ceilings, which allowed for measuring the wall-ceiling joint, where leakage was found to be negligible.

Shaw, C.Y., S. Gasparetto, and J.T. Reardon, “Methods for Measuring Air Leakage in High-Rise Apartments,” *STP 1067 Air Change Rate and Airtightness in Buildings* (American Society for Testing and Materials [ASTM], Philadelphia, PA), pp 222-229.

This paper describes the use of a modified fan depressurization technique to measure the overall exterior leakage of a high-rise apartment building and the exterior wall of an individual apartment simultaneously. This was done for two different co-located buildings. The purpose for conducting these tests was to assess the effectiveness of retrofit measures in reducing air leakage in the buildings. Thus tests were run before and after the retrofits and then compared.

The test method is described in detail in the paper. To accomplish the depressurization of the large buildings, a vane-axial fan, capable of producing flows up to 50,000 cfm, was used. A small fan depressurization unit was used for the single apartment. A key to the method and getting valid readings for the exterior wall of the single apartment was to achieve a pressure balance (zero pressure differential) between the test unit and adjacent apartments. This was done to minimize air leakage through the common walls as well as horizontally in the exterior wall cavity in local vicinity.

Based on the findings, the evidence suggests that the air leakage through exterior walls is not as much as through the roof and basement.

Sherman, M.H., and L.E. Palmiter, "Uncertainties in Fan Pressurization Measurements," *STP 1995, ASTM Symposium Air Flow Performance of Building Envelopes, Components and Systems 10-11 October 1993, Dallas TX*.

This paper analyzes the precision and bias associated with making air leakage measurements using the fan pressurization method described in ASTM E 779 under typical field conditions. This uncertainty into the process is attributed to precision errors due to noise and other random error, biases (systematic departures from the true value) in the measurement of airflow and pressure, and extrapolation (monetization) errors in estimating the effective leakage area at a 4 Pa pressure differential. The extrapolation for determining the ELA at 4 Pa is necessary because the fan pressurization technique cannot directly measure flow at the low pressure differential.

Based on the study, the researchers propose an improved measurement procedure that includes instrumentation specifications, experimental procedures and analyses methods to be used. Specific recommendations include:

- Use flow-measuring device that is unbiased to within 2 percent of reading and has an intrinsic precision error of less than 5 percent of the reading
- Use pressure-measuring device that is unbiased to within 5 percent of reading, with an intrinsic precision error within 5 percent of reading or 1 Pa.
- Make time-averaged measurements at each pressure station to reduce noise. This can be accomplished by making multiple measurements and averaging as part of the data analyses or having the instrumentation average the measurements during testing.
- Use an optimized test design that includes a small number of pressure stations (i.e., 10, 15, 25, 50 Pa) and a weighted regression analysis.

Tamura, G.T., and C.Y. Shaw, "Studies of Exterior Wall Air Tightness and Air Infiltration of Tall Buildings," *ASHRAE Transaction 82* (1976), vol 1.

This paper discusses the methodology of using the building ventilation system to conduct fan pressurization air leakage tests on tall buildings and provides actual case study results. The National Research Council of Canada took air leakage measurements of exterior walls of 8 multi-story office buildings located in Ottawa. Their heights ranged from 11 to 22 stories. To accomplish the air leakage measurement, the supply air rates provided by the system were varied and the coefficients and exponents of the flow-pressure equations were determined. The paper also discussed stack effects and pressure differences. It was noted that the calculation of infiltration rates caused by wind is complex and must account for the wind pressure distribution over the surface of the building; which is dependent on the wind speed and direction, building shape and surroundings.

## 8 Conclusions

This literature search shows an emerging academic research for internally released CBR agents. Principle research tracks included dispersion of CBR agents within a facility and the transport of agents into a facility from outside release. The science for both of these tracks is currently very limited. Significant advances must be made to meet the September 2002 Deputy Secretary of Defense guidance for personnel protection. Furthermore, there is no published research on intelligent building controls as related to CBR protection. Lastly, the traditional heating, ventilation, and air-conditioning (HVAC) industries are in a “wait and see” mode; when it comes to CBR protection; they are not motivated to advance the state of science beyond indoor air quality and energy efficiency performance. If “life safety” is to be assured, then government needs to step up and aggressively take the lead. Collaboration between the National Energy Labs and the DOD labs is emerging as the government response for this needed research.

Principle technology gaps in need of research by the DOD include:

1. Computational Fluid Mechanics (CFD) based modeling and simulation. CFD modeling of concentration profile around a building envelope, realistic modeling of complex physical configuration inside a building, and modeling of HVAC components and operation are the challenging tasks under active study currently.
2. Building Automation Systems (BAS) and Life Safety Systems must be integrated to provide full-spectrum CBR protection. Research is needed to provide a communications protocol that supports these traditionally independent systems.
3. Also, the BAS must facilitate an increased level of protection compared to today's energy-efficiency-focused systems. Research is needed to advance its capability to autonomously monitor and control the building's sensors, pressures, flows, equipment on/off status and through its ability to shutdown systems, turn on/off fans, pressurize spaces/zones, and control air flow.
4. There is no established protocol for determining the building envelope leakage parameters, which is necessary for providing the boundary conditions for CBR contaminant transport modeling. Nor does a process exist for assessing these parameters during a building's service life, which is a requirement for ensuring that any enacted building response is based on an accurate model.
5. While limited automated HVAC diagnostic systems exist, no automated diagnostic system is known to exist for assessing the performance of an installed CBR

protective system over a facility's life. Thus, CBR-focused diagnostics research is needed.

## Appendix A: General Bibliography

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14. ABSTRACT  Department of Defense policy is to protect all military and civilian personnel on military installations against chemical, biological, radiological, nuclear, and high-yield explosive (CBRNE) attacks, specifically “to protect personnel on military installations and DOD-owned or leased facilities from CBRNE attacks, to respond to these attacks with trained and equipped emergency responders, and to ensure installations are able to continue critical operations during an attack and to resume essential operations after an attack.  Compliance with this memorandum, however, will be an enormous undertaking. Existing technologies that will enable DOD to fully implement its CBRNE protective policy must be identified and validated. Technology gaps in DOD’s ability to respond to and resist specific CBR threats must be identified, and solutions that fill those gaps must be developed. This work summarizes past and current re-search in target technological areas, with a focus on three CBR protection sub-areas: (1) modeling and simulation of airborne chemical/biological contaminant dispersion in a building, (2) intelligent building control, and (3) CBR-related whole building diagnostics.						
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